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Identifying Periods of Financial Stress in Asian Currencies: The Role of High Frequency Financial Market Data*

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Abstract

We formally test that a process containing Brownian motion and jumps characterises the high frequency observations for eight Asian currencies against the US dollar. By harnessing the changes in behaviour of the data during periods of stress we develop a new indicator to detect stress dates in currency markets. We find that the global share of currency trade for each currency relates to the frequency of stress days detected. We align the stress dates to economic and political conditions using central bank and IMF reports on developments in currency markets.

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1 Introduction

The high frequency behaviour of asset prices is important in correctly determining the pricing of derivative products, assessing market efficiency and hedging strategies particularly through estimating and forecasting volatility; Andersen et al (2007, 2011), Zhang et al (2009), Dungey and Hvozdyk (2012). The presence of price discontinuities, or jumps, contaminates measures such as realized volatility, and markets may well react differently to movements caused by jumps than those from an underlying continuous process; Todorov and Bollerslev (2010)[1]. Aït-Sahalia and Jacod (2008,2009,2010,2012) have developed a suite of tests to detect the characteristics of univariate high frequency series. To date, these tests have been applied to developed, liquid markets and support the presence of jumps and Brownian motion in assets such as stocks of the Dow Jones 30, US Treasuries, and the exchange rates of the Euro and Yen against the US dollar (Aït-Sahalia and Jacod 2012, Dungey et al 2012 and Erdemlioglu et al 2013).

This paper provides a first characterisation of these high frequency properties for emerging market currencies. Emerging market currencies are of increasing importance to the global economy; 27.5 percent of the currency transactions recorded for the BIS(2013) triennial global exchange turnover survey involved an emerging market currency.[2] Transactions between the Chinese Renimibi-yuan and US dollar alone accounted for 2.1 percent of recorded turnover. The volume of transactions in these currencies, and expanding derivatives markets, necessitate a stronger understanding of how their behaviour potentially differs from the more studied developed markets. Using the Aït-Sahalia and Jacod statistics we examine the high frequency characteristics for the US dollar exchange rates of a group of eight Asian currencies, including both emerging and developed markets for a sample from 1996 to 2013.

Our work extends to assess the high frequency characteristics of currencies

[1] Although Patton and Verardo (2012) show that estimates of realized beta are not driven by jumps in prices ocurring on announcement days.

[2] Figure compiled from Table 3 in BIS(2013); classifying transactions for developing economy currencies against USD,JPY,EUR,GBP,AUD,CAD,CHF,NZD and SGD.

during periods of calm and periods of stress and shows that there are systematic differences in the distribution of the jump detection statistics during periods of stress. During periods of stress, the jump detection statistics are more able to differentiate jumps from noise than during periods of calm – a finding which remains consistent with recent evidence that the frequency of jumps does not alter during periods of crisis in recent papers; Catrath et al (2014), Black et al (2012), Novotný et al (2013).

We implement a new measure for detecting stressful periods using the characteristics of high frequency data. Based on the jump detection methods using tail observations, we propose a ratio statistic that identifies the jump arrival dates when market conditions change. The structure of the measure is related to the existing currency stress detection work on the exchange market pressure index originating with Eichengreen et al (1996). As in that literature we determine stress dates as exceedances over a pre-determined threshold. We then align those stress dates to the events of the identified periods using quarterly and annual reports from central banks and IMF reports for the individual countries.

This paper shows that high frequency data can reveal periods of significant stress in emerging currency markets. Changes in the behaviour of the data generating process of this data occur in a manner which can provide timely warning of stressful conditions to market participants and regulators. The conventional approach to detecting financial market stress and early warning systems largely relies on lower frequency data available as either real macroeconomic indicators or balance sheet data; Claessens and Kose (2013) provide an overview. Dating crises with low frequency data has the advantage that it is able to detect the presence of real economy effects, so that it is clear when a crisis has become economically costly. However, the use of high frequency data is predicated on the idea that it is possible to calm market conditions before a full-blown crisis emerges - the premise underlying the suite of indicators proposed in the IMF-FSB Early Warning Exercise; see IMF(2010). Intraday data are now in use for the measurement of systemic risk in the banking sector such as Dungey et al

(2013), Brownlees and Engle (2012), Diebold and Yilmaz (2011).[3]

Our results show that each of the eight exchange rates exhibits behaviour consistent with the presence of jumps and Brownian motion in both calm and crisis periods of the sample. This result is consistent with the literature on US stock and fixed-income markets in Aït-Sahalia and Jacod (2012), Dungey et al (2012) and confirms the results for the yen/US dollar exchange rate in Erdemlioglu et al (2013). The evidence for infinite activity jumps is more mixed at standard levels of statistical significance. The characteristics of the distribution of the jump detection statistics changes dramatically between pre-identified periods of financial stress and periods of calm. Specifically, during periods of stress the kurtosis of the distribution increases dramatically – interpretable as a far greater ability to distinguish jumps from noise during periods of stress.

We apply a rolling index of jump detection statistics to tail returns and use it to indicate stressful events when a pre-determined threshold is exceeded. There is a large discrepancy between the number of days highlighted for different currencies, ranging from only 5 days in Japan and India to 26 in Malaysia. Our alignment of the identified stress dates with central bank reports and the BIS triennial surveys on exchange rate turnover suggests a number of important influences on the relative frequency of stress days.

The currencies with greater volume of trade experience fewer stress incidences, although we are unable to extend this to matching with daily or transactional volumes due to lack of data on currency volume at higher frequencies. These effects are potentially related to liquidity effects. There is no evident alignment between the frequency of stress days and the exchange rate regime. However, fewer stress days are observed for developed markets than for the majority of the emerging markets. The case of India is a particularly interesting exception to this; the rapid growth of volume in the Indian rupee, of over 60 percent per annum from 1998 to 2013 (BIS, 2013) seems to have protected it

[3] Daily data are used in detecting crises and bubbles in Wang and Nguyen Thi (2013), Addo et al (2013) and Phillips and Yu (2011) and there is a considerable literature on developments in lower frequency literature such as Phillips et al (2012) who provide a test for multiple bubbles in monthly data.

from exhibiting as much stress as other developing markets, although the significant turmoil in its internal financial markets in 2001 is clearly evident. In the developing markets, stress relating to important political developments is also present. An appealing feature of the stress measure proposed here is that it clearly indicates specific periods of stress. Unlike measures of exchange market pressure developed in Eichengreen et al (1996) and its descendants, our results do not rely on ad hoc truncation windows to reduce the number of stress signals; Jacobs et al (2005) overview the truncation rules used in a number of exchange market pressure papers.

The paper proceeds as follows. Section 2 outlines the statistics which characterize the data generating process of high frequency univariate price series. The dataset of eight exchange rates is briefly outlined in Section 3. The empirical results for the characteristics of this data for the full sample and during pre-identified periods of calm and stress are reported in Section 4. Drawing on this evidence we develop the approach to identifying stressful days using rolling statistics with which we identify stress dates for each exchange rate and relate this to recorded events. Section 5 concludes.

2 Modelling Framework

Assume that the price for an individual asset denoted X_t, evolves as follows:

$$\begin{aligned} X_t &= X_0 + \int_0^t b_s ds + \int_0^t \sigma_s dW + \\ &\quad \int_0^t \int_{[|x| \leq \varepsilon]} x(\mu - v)(ds_x, dx) + \int_0^t \int_{[|x| > \varepsilon]} x\mu(ds_x, dx) \end{aligned} \quad (1)$$

which is a semimartingale of the form proposed by Aït-Sahalia and Jacod (2009,2010,2012). It comprises a non-zero mean, drift, Brownian motion and two potential jump components – one representing small (infinite) jumps and the other larger (finite) jumps, separated by a threshold, ε. Over a stream of papers, Aït-Sahalia and Jacod (2008,2009,2010,2012) propose a number of statistics to determine which of these potential processes are evident for an univariate high frequency series. As is usual, we work in the discrete version of this process, examining the behavior of $\Delta_i^n X$, which represents the intra-period return for the i^{th} period in the n intraday observations over T days.

A well-known statistic for high frequency data is the volatility proxy, realized volatility, given as the sum of squared intra-daily returns;

$$RV = B(2, \infty, \Delta_n) = \sum_{i=1}^{T/\Delta_n} \left|\Delta_i^n X\right|^2 . \tag{2}$$

However, this can be extended to higher powers, and for $p \geq 2$ we may write

$$B(p, \infty, \Delta_n) = \sum_{i=1}^{T/\Delta_n} |\Delta_i^n X|^p . \tag{3}$$

Further, we can also consider this statistic for a truncated section of the distribution – Aït-Sahalia and Jacod (2010) suggest truncating the tails, and introducing a truncation value u_n, such that when $|\Delta_i^n X| > u_n$ the observation is omitted from the statistic. We denote this as follows:

$$B(p, u_n, \Delta_n) = \sum_{i=1}^{T/\Delta_n} |\Delta_i^n X|^p \, 1_{\left\{|\Delta_i^n X| \leq u_n\right\}} \tag{4}$$

It turns out that we have three tools with which to describe the behavior of high frequency financial series; the power of the function given by p, the truncation choice, u_n, and additionally sampling frequency. Denoting the baseline sampling frequency as $k = 1$, we can then denote other frequencies using k, for example

$$B(p, u_n, k\Delta_n) = \sum_{i=1}^{T/\Delta_n} |k\Delta_i^n X|^p \, 1_{\left\{|k\Delta_i^n X| \leq u_n\right\}}. \tag{5}$$

2.1 Statistics

We adopt three of the statistics to describe the behavior of high frequency data generating processes developed in Aït-Sahalia and Jacod (2009,2010) to detect the presence of jumps and Brownian motion respectively. These statistics lead naturally to a complementary measure first proposed in Dungey et al (2012) to detect the presence of large (positive and negative) jumps. To detect whether a series contains statistically detectable jumps (or discontinuities) consider the following:

$$S_J(p, \infty, k, \Delta_n) = \frac{B(p, \infty, k\Delta_n)}{B(p, \infty, \Delta_n)}. \tag{6}$$

The basis of the S_J statistic is that sampling the data at two different frequencies, $k = 1$ and $k > 1$ (usually k is an integer, although this is not strictly necessary), should reveal permanent discontinuities. This statistic is defined for $p > 2$, and is applied across the entire distribution of returns (that is $u_n = \infty$). Theoretically, in the absence of noise, this statistic converges as follows (see Aït-Sahalia and Jacod, 2012):

$$S_J\left(p, \infty, k, \Delta_n\right)_t \xrightarrow{p} \begin{cases} k^{p/2-1} & \text{no jumps} \\ 1 & \text{jumps} \end{cases}$$

The second statistic detects the presence of Brownian motion as the continuous component of the series. In this case the data are assessed by sampling at two different frequencies, but with truncated distributions. That is, S_W is an inverted truncated analogy to S_J, assessed over $p < 2$ and $k \geq 2$.

$$S_W\left(p, u_n, k, \Delta_n\right) = \frac{B(p, u_n, \Delta_n)}{B(p, u_n, k\Delta_n)} \tag{7}$$

The theoretical distribution of this statistic in the absence of noise is given in Aït-Sahalia and Jacod (2012) as follows:

$$S_W\left(p, u_n, k, \Delta_n\right)_t \xrightarrow{p} \begin{cases} k^{1-p/2} & \text{Brownian motion present} \\ 1 & \text{No Brownian motion} \end{cases}$$

The truncation u_n is selected as $u_n = \alpha\sqrt{BV_t}\Delta^{\omega}$ where BV is bipower variation

$$BV = \frac{\pi}{2}\left(\frac{T/\Delta_n}{T/\Delta_n - 1}\right)\sum_{i=1}^{T/\Delta_n} \left|\Delta_i^n X_i\right| \left|\Delta_i^n X_{i-1}\right|$$

and $\alpha > 0$ and $\omega \epsilon (0, 0.5)$.

The third statistic S_{FA} detects whether the series has finitely / infinitely many jumps on the time interval. For $p > 2$ and $k \geq 2$, the limiting behaviour of the following ratio

$$S_{FA}\left(p, u_n, k, \Delta_n\right) = \frac{B(p, u_n, k\Delta_n)}{B(p, u_n, \Delta_n)}$$

determines whether jumps have finite or infinite activity. According to Aït-Sahalia and Jacod (2012),

$$S_{FA}\left(p, u_n, k, \Delta_n\right)_t \xrightarrow{p} \begin{cases} k^{p/2-1} & \text{finitely many jumps} \\ 1 & \text{infinitely many jumps} \end{cases}$$

The asymptotic variances of these statistics in order to provide standardized statistics (normally distributed with zero mean and unit variance) are described in Aït-Sahalia and Jacod (2008,2009,2010).

To examine the the behavior of the tails of the distribution, Dungey et al (2012) propose a complementary statistic to indicate the presence of large jumps:

$$S_{TI}\left(p, u_n, k, \Delta_n\right) = \frac{\sum_{i=1}^{T/\Delta_n} \left|k\Delta_i^n X\right|^p 1_{\left\{\left|k\Delta_i^n X\right| > u_n\right\}}}{\sum_{i=1}^{T/\Delta_n} \left|\Delta_i^n X\right|^p 1_{\left\{\left|\Delta_i^n X\right| > u_n\right\}}} \tag{8}$$

with $p > 2$ and $k \geq 2$.

This statistic includes both negative and positive tails. We may also calculate positive and negative indicators for the cases where $S_{TI}^{+}\left(p, u_n, k, \Delta_n\right)$ is limited to the cases where $\Delta_i^n X > u_n$ and $S_{TI}^{-}\left(p, u_n, k, \Delta_n\right)$ is limited to the cases where $\Delta_i^n X < -u_n$. As will be shown in the following section, it is the changes in this statistic which are informative about periods of stress.

3 Data

Data are sourced from the Thomson Reuters Tick History (TRTH) database, provided through SIRCA for the sample period January 1, 1996 to April 10,

2013. We collate 5-minute returns for the following eight currencies against the US dollar: Australian dollar, Indian rupee, Indonesian rupiah, Japanese yen, Korean won, Malaysian ringgit, Singaporean dollar and Thai baht – 5-minute returns are currently the standard approach in assessments of behavior in financial markets; for example the recent papers of Catrath et al (2014), Black et al (2012), Novotný et al (2013), Hanousek and Novotný (2012). Although the foreign exchange market is open 24 hours a day, 7 days a week, we exclude data from 00:00GMT Saturday to 24:00GMT Sunday due to thin trading. Days with excessive missing values are also removed (common examples include Christmas Day in some countries), otherwise where no trade occured within a 5 minute interval a zero return was recorded. As holidays and missing data can vary with the domestic country the number of observations is slightly different for each exchange rate, but in general the complete sample results cover 4492 days and over 1.2 million observations for each currency. The exact numbers are given in Table 1.

4 Empirical Results

We estimate the values of the Aït-Sahalia and Jacod S_J, S_W, S_{FA} statistics for every day in the sample. Following Aït-Sahalia and Jacod (2012) and Erdemlioglu et al (2013), we apply the values of $p = 4$ and $k = 2$ for S_J, S_{FA}, S_{TI}, S_{TI}^{+}, S_{TI}^{-} and $p = 1$ and $k = 2$ for S_W. The truncation thresholds, u_n, uses $\omega = 0.47$ and $\alpha = 8$ for S_W, S_{FA} and $\alpha = 2$ for S_{TI}, S_{TI}^{+}, S_{TI}^{-}. Table 1 presents the mean, median, standard deviation and kurtosis of the statistics for each exchange rate. The presence of outliers in some currencies significantly affects the statistics; thus Table 2 contains the same information when outliers of value larger than 10 are excluded.

Consider first the S_J statistics for each exchange rate. The median statistics, both including and excluding outliers, are around 1, consistent with jumps. This is supported by the result for the average of the formal standardized statistic reported in Table 3 which accepts the null hypothesis of the presence of jumps.

The histograms for the S_J statistics for each of the individual exchange rates are shown in Figure 1. Aït-Sahalia and Jacod (2012) show how the distribution of these collected statistics are readily interpretable – the expected mass of S_J at value 1 is associated with the presence of jumps, mass to the left is associated with noise, and mass far enough to the right (with $k = 2, p = 4$, this is around $k^{p/2-1} = 2$) indicates the absence of jumps. Each of the currencies are clearly modal at 1, supporting the presence of jumps, and once the outliers are removed the standard deviations of these distributions (compare Tables 1 and 2) are relatively similar. However, they differ in the degree of kurtosis. The Australian, Japanese and Singaporean currencies all have kurtosis lower than 10, once outliers are accounted for in Table 2, while kurtosis in other currencies are as high as 55 in the Indian case. With reference to these distributions kurtosis has a useful interpretation – the more leptokurtic the distribution the more easily the non-standardized S_J statistic will accept the null of jumps in the system. That is, jumps are easier to differentiate from noise (whether or not there are different numbers of jumps present).

The S_W statistics, reported in Tables 1 to 3, also support the presence of Brownian motion for all currencies. With $k = 2, p = 1$, the value of S_W consistent with Brownian motion is $k^{1-p/2} = 1.4142$, and all of the results reported in Tables 1 and 2 show that the S_W from the distributions with and without outliers removed are consistent with this. The standardized test statistics reported in Table 3 fail to reject the null of the presence of Brownian motion. Figure 2 shows the distributions of the S_W statistics (without outliers) for each of the exchange rates, where each distribution is modal around $k^{1-p/2}$. Mass to the left of this, around 1, represents the alternative of no Brownian motion and no noise. (Mass even further left again at $1/k = 0.5$ represents the case where additive noise dominates. In all the cases represented in Figure 2 there is no mass consistent with additive noise; see Aït-Sahalia and Jacod 2012).

The S_J and S_W statistics have previously been used to test for the presence of jumps and Brownian motion in the 30 components of the Dow Jones Industrial Average (Aït-Sahalia and Jacod, 2009, 2012; where the analysis is conducted on the pooled results, not by individual assets), for Brownian motion in Microsoft and Intel stocks in Aït-Sahalia and Jacod (2012) and for the Japanese yen and Euro exchange rates against the US dollar in Erdemlioglu et al (2013), each of which supports these assets as having Brownian motion and evidence for jumps. Thus, our results supporting the presence of jumps and Brownian motion in all eight exchange rates are consistent with the existing evidence.

We now turn to the question of whether there is evidence of infinite jump activity as found for stocks in Aït-Sahalia and Jacod (2012). Tables 1 and 2 present the mean and median values of S_{FA} with and without outliers removed. These statistics should converge to 1 under the null of infinite jumps and $k^{p/2-1} = 2$ under the alternate of finite jumps. The tables and the histograms of each exchange rate in Figure 3 support the null. However, the standardized test results in Table 3 do not uniformally fail to reject the null hypothesis of infinite activity in all currencies at the usual significance levels. While the Indian, Indonesian, Japanese, Korean and Malaysian exchange rates fail to reject infinite activity jumps at a 5 percent significance, the Australian exchange rate is significant at 3 percent and the Thai exchange rate at 1.4 percent. Much of the jump testing literature imposes much higher than usual significance for test rejection (commonly at 0.1 percent such as in Andersen et al 2007, Dungey et al 2009), and we would have to adopt similarly small thresholds in order to conclude that all the exchange rates examined here displayed infinite activity jumps. The Singaporean exchange rates would only fail to reject the null of infinite activity at a significance level of 0.39 percent. These mixed results present an interesting new finding, differentiating these currencies. Two of the currencies which reject the null at 5 percent are from developed markets – Australia and Singapore, of which one is a clean float and the other is managed – and one is Thailand which has a fixed regime during part of the sample.

4.1 Periods of Stress versus Periods of Calm

To understand how the characteristics of the high frequency exchange rate data may change during periods of stress we compare exogenously identified periods of financial stress with periods of calm. We identify periods of stress from the daily realized variance (RV) computed from the 5 minute data across the sample for each of the 8 exchange rates. Table 4 reports the S_J, S_W, S_{FA} statistics for the calmest periods in each exchange rate selected using a 90 day rolling window of average daily RV. Table 5 reports these statistics for the most volatile period selected in the same manner. Tables 6 and 7 report results for further instances of volatility for each currency. These were selected by examining the RV data for periods of sustained volatility and choosing the 90 day window with the highest volatility.

Comparing across Tables 4 -7, the first point to note is that the evidence for Brownian motion and infinite activity jumps, S_W and S_{FA}, is unaffected by whether the sample application refers to a calm or crisis period.

The S_J test statistics for each of the 8 currencies for periods of calm and stress are consistent with the presence of jumps in each currency in each period. However, the kurtosis computed from the S_J statistics during periods of stress is higher than the kurtosis computed from data sampled during periods of calm, for 7 of the 8 currencies. The exception is Thailand, which may be explained by the fixed peg regime the currency had until 1997, which makes the calm period an atypical period - thus the two last columns in the bottom panel of Table 4 present statistics for Thailand including and excluding the fixed peg currency regime.

The change in skewness of these statistics is consistent with the presence of crisis conditions in the underlying data, Fry et al (2010), although the properties with the S_J transformation of this data are not as notable as in the US Treasuries market, Dungey et al (2012). The importance of the increase in kurtosis of these S_J statistics is that they indicate that during periods of stress the jumps are more easily detected - the mass of these statistics is more clustered around 1. That is, although the number of jumps may not change as evidenced elsewhere in the literature, during stressful periods the data generating process alters in a way that means jumps are more readily detected from noise. This provides useful properties for the timely detection of periods of stress.

There has been considerable debate about the role of jumps in asset prices during periods of financial stress. Extreme movements, and increased correlation, are stylized features of periods of financial stress, as used in the literature on co-exceedances and copulas to capture contagion effects; see for example Bae et al (2003), Baur and Schulze (2005) and Busetti and Harvey (2011). However, tail movements and jumps are not necessarily coincident concepts. Barada and Yasuda (2012) and Novotný et al (2013) both demonstrate that there is not greater incidence of jump activity during crisis conditions. Hanousek and Novotný (2012) conclude that there is therefore no need to control for jump behaviour in stress testing volatility under Basel III.

That the S_W and S_{FA} statistics do not change much - indicating that the evidence for the presence of Brownian motion is similar in both periods - but that S_J is somewhat different leads us to consider the difference between these statistics. Reference to equations (6) and (7) makes it immediately apparent that the truncation choice is the important difference between them. Logically, given that between stressful and calm periods, S_J changes and S_W does not, then the changes are occuring in the truncated section. That is, we can make use of the statistic proposed in Dungey et al (2012), which takes advantage of the extreme returns – that is those which are captured in S_J but not in S_W – using the S_{TI} statistics outlined in equation (8). We report the values of this statistic, and the positive and negative tail analogues S^+_{TI} and S^-_{TI} in Tables 1 and 2 (to conserve space we present only the S_{TI} histograms - Figure 4), which show that as expected the mass in each case is centred around 1, supporting the presence of both large positive and large negative jumps. However, our interest is centred more on using the changes indicated by these statistics through time than analysing these individual statistics.

To capture the potential for rapid change from calm to stressful conditions we implement rolling ratios of the value $S_{i,TI,t}/S_{i,TI,t-1}$ on a daily basis to pick up days where the extreme returns are sufficient to demonstrate particular stress in each currency. We hence consider the ratio:

$$S_{i,t} = \frac{S_{i,TI,t}}{S_{i,TI,t-1}}$$

where $S_{i,t}$ picks up periods of stress associated with changes in the value of the domestic currency. The upshot of this statistic is that when nothing changes between periods then $S_{i,t} = 1$. Analagous ratios can be calculated for the signed tails: $S_{i,t}^{+}$ and $S_{i,t}^{-}$.

As a threshold value for detecting stressful periods we adapt the approach common in the crisis detection literature of identifying a crisis when the $S_{i,t}$ index exceeds some confidence band beyond its median; see for example Eichengreen et al (1996). That is creating a binary variable with the value of 1 for a period of stress as follows:

$$Stress_{i,t} = \begin{cases} 1 \text{ when } |S_{i,t}| > \widetilde{s_i} + \theta\sigma_{S_i} \\ \quad 0 \text{ otherwise} \end{cases} \tag{9}$$

where $\widetilde{s_i}$ is the median and σ_{S_i} is the standard deviation of the ratio S_i for currency i. The choice of θ determines the coverage of the distribution, where $\theta = \{1, 2, 3, 4\}$ imply $\{68\%, 95.5\%, 99.7\%, 99.9\%\}$ confidence bands respectively. Eichengreen et al (1996)[4] apply $\theta = 3$, but it is also common in high frequency data to consider $\theta = 4$ in testing for discrete jumps; see for example Dungey et al (2009), Lahaye et al (2011).

4.2 The Stress Indices

Table 8 tabulates the number of exceedances of S_{TI} above threshold for each currency across four different thresholds, $\theta = \{1, 2, 3, 4\}$ and two potential values of σ. The first panel provides results when σ includes all the outliers in the sample, and unsurprisingly produces the smallest number of stress dates. The central panel reports exceedances with σ excluding outliers where $S_{i,t}$ exceeds 1000. The final panel combines the dates in the top and central panel - it is

[4] Eichengreen et al (1996) use the mean, but due to the high evidence of outliers we replaced mean with median.

apparent that only a few dates from the top panel were not incorporated in the central panel.

When outliers are included the exchange rates with the fewest exceedances are the Australian dollar and Malaysian ringgit, with no more than 0.20 percent exceedances at $\theta = 1$ and fewer than 0.10 percent at $\theta = 4$. India and Japan both have 0.11 percent exceedances at $\theta = 4$, while Indonesia, Korea and Singapore are clustered just over 0.20 percent. The highest proportions of exceedances at all levels are found in the Thai exchange rate (0.29 percent).

After excluding outliers in calculating the critical threshold level the results change considerably for some exchange rates (as shown in the central panel). These results are carried into the final panel, and our discussion centres around those results. The exchange rates with the fewest exceedances at $\theta = 4$ are the Japanese yen and the Indian rupee, which have around 0.11 percent periods of stress in the sample. The Singaporean and Australian dollars have just over 0.2 percent in stress, with the Korean won just over 0.3 percent. The least developed and relatively smaller markets for the Indonesian rupiah, the Thai baht and Malaysian ringgit have the most exceedances - with the Malaysian ringgit substantially more than the other rates at 0.72 percent. These relative rankings are maintained through the different thresholds considered.

These rankings lend themselves relatively readily to analysis based on the global volume of trade in these currencies. Table 9 provides the proportion of global turnover in each of the currencies included in our sample from the BIS (2013) triennial survey of currency transactions. The Japanese yen is the third most traded curency in global turnover at 23 percent of total turnover in 2013 (behind the US dollar and the Euro), and has been in this position since the introduction of the Euro (see Table 2, BIS 2013). The Australian dollar is the fifth most traded at 8.6 percent of turnover, a position it took over from the Swiss franc in 2007. (In our sample only the Japanese yen and Australian dollar have reportable volume of trade with currencies other than the US dollar.) The next highest ranked of our currencies in terms of global turnover is the Singaporean dollar as 15th most traded and 1.4 percent of total global turnover in 2013. Thus, the three currencies with the highest volume in our sample are clustered towards the lower end of the exceedances, suggesting a role for turnover. (It is unfortunately not possible to obtain daily volume on currency transactions to match our price observations to provide a more detailed analysis of the role of volume.) The Malaysian, Thai and Indonesia currencies all accounted for less than 0.4 percent of total turnover in 2013 - ranking 25th, 27th and 30th respectively, and were those who recorded the largest numbers of periods of stress. The intermediate ranking of the Korean won is also reflected in its ranking as the 17th most traded currency with 1.2 percent of global turnover in 2013.

While the association of turnover and stress exceedances is convincing, the Indian results do not fit this scenario. The market for Indian rupee has grown ten-fold since 1998, from 0.1 percent of global turnover (or \$US1.7 million) to 1.0 percent (or \$US53.4 million equivalent) in 2013. This represents an average annual growth rate of 60 percent in an environment where the total market grew by under 15 percent per annum. Turnover in the Indian rupee is the highest growing recorded by BIS with the exception of the Chinese Renimbi-yuan which had no discernible volume recorded in 1998 but was the 9th most traded currency in 2013, and matched only by the rise in the volume of New Zealand dollar transactions from 0.2 to 2.2 percent of volume. The rise of the Indian financial market over our sample period is dramatic.

4.3 Stress Dates

Table 10 and Figure 5 provide the dates associated with exceedances of the 3 and 4 standard deviation thresholds for each currency in the sample, corresponding to the last rows of each section of Table 8. The superscript 4 indicates where the 4 standard deviation threshold was exceeded. As we have calculated two potential candidates for σ in calculating the stress dates in equation (9), in Table 10 we differentiate stress dates identified only with the threshold calculated without outliers by *, and those which occurred only when outliers were included by **. When no stars are present both thresholds were exceeded. Thus in Table

10 and Figure 5, for Thailand, the date Jan 24, 1996 exceeded the four standard deviation threshold when outliers were excluded in the calculation of σ, and the date Oct 7, 2004 exceeded the four standard deviation threshold using both calculations of σ. We also record where the same dates were evident in the signed stress indicators constructed as $S_{i,t}^{+}$ and $S_{i,t}^{-}$. That the days associated with negative tail volatility are 50% more numerous than those associated with positive tail volatility indicates that stress is more often generated by negative large jumps.

Using central bank quarterly and annual reports and IMF country reports in what follows we relate the chronology of the periods to the stress dates exceeding the 4 standard deviations in Table 10 (and Figure 5) for each currency. First it is useful to note that there is no evidence of clustering across the different exchange rates consistent with a common US based event driving the stress days. There is some clustering in the Asian economies, particularly for Thailand in 1998 consistent with the Asian crisis. There is also a cluster of activity in 2001, which may be consistent with the dot-com bust that year. However, as will be shown, the individual country-based analyses are more convincing. The emerging Asian currencies do not fluctuate as much with respect to US and European shocks, but rather are concerned with regional and local conditions.

4.3.1 Australia

The Australian results include 11 dates on which the four standard deviation threshold is exceeded. The first of these on August 28, 1998, corresponds to the fall out from the Russian debt-default, the end of the speculative double-play on the Hong Kong dollar and the first signs of the unravelling of the hedge fund Long-Term Capital Management. This is a particularly complex period which involved the Australian currency via its exposure to the US Treasury markets and commodity markets; see Dungey et al (2007) for an analysis. In March and May 1999, improving economic conditions, the breakthrough of the US Dow Jones index past both the 10,000 and 11,000 levels, stronger commodity prices and an increase in long term yields associate with the stress index.

In 2000, the Australian dollar behaved in a way not previously seen - falling in the face of improving domestic economic conditions, and by over 10 percent in trade-weighted terms during that year. In the early part of the year the Australian dollar fell on news associated with expected relative increases in US interest rates, weakening in the domestic economy and uncertainty about the retail impact of the Olympic games hosted in Sydney that year - including a fall of over one cent in the value of the Australian dollar against the US dollar. In the second half of the year investor sentiment focussed on new-technology led growth, and disengaged from so-called old-economy investment opportunities in Australia. These events are analysed in detail in MacFarlane (2000) and RBA (2000).

Stress events in 2001 are all associated with the dot-com collapse, and the reversal of the fall-out from being classified as old-economy stocks in the previous year.

The next exceedances of the 4 standard deviation threshold for the Australian exchange rate occur in the first half of 2010, and these are broadly associated with the deteriorating conditions in European debt markets and behaviour in commodity markets. The Australian dollar had hit a low against the US dollar in February 2009, and began recovering thereafter although exhibiting historically relatively high volatility (RBA 2010). In late 2010 the Australian dollar hit parity with the US dollar, and in late December the East coast, particularly Brisbane, was hit by substantial flooding which had a significant economic impact on the economy.

4.3.2 India

There are 5 stress days identified in the Indian data, of which four indicate stress in the negative tail. The first of these is in June 1999 and corresponds with the Kargil conflict between Pakistan and India between May and July 1999. Combined with a no-confidence vote in the Lok Sabha in April 1999, and subsequent elections in the last quarter of the year, the external conditions facing the country were described as challenging in the mid-term 1999-2000 review of the Reserve Bank of India; RBI (1999).

The stress evident in India in 2001 is consistent with the crash in Indian stock markets and financial problems resulting from previous highly leveraged positions premised on ever-rising stock prices built on the dot-com boom. Subsequently Indian credit ratings were downgraded in November 2001. In early 2002 India faced poor economic news and political tensions in the Indian-Pakistan border and the Gujarat riots. Following a tightening in Indian monetary policy in April 2007, in early August of that year the effects of the developing credit crunch emanating from the US led to a large decline in the Indian stock market and an indicator of worsening conditions in the first quarter of 2008. Since that point the Indian currency markets seem not to have been subject to stress resulting from the European debt crisis.

4.3.3 Indonesia

The 18 Indonesian exceedances largely correspond with Indonesian events in the first part of the sample. The first exceedance, in April 1996, followed strong growth results on the heels of earlier concerns about the high inflation rate and current account deficit in the economy. In early 1998, in the lead up to the Asian crisis, President Suharto finally succumbed to pressure to resign on May 21 and the news was dominated by the poor economic outlook, including in December 1998 news that the economy shrank by over 13 percent that year with inflation of over 75 percent. During 1998 the rupiah depreciated by almost 30 percent. In late 1999 the country was again under pressure at the end of the year associated with the upcoming audit of the IMF program in December, a process which had been hampered by the violence associated with the independence vote for East Timor.

The year 2000 saw an improved economic assessment by the World Bank and further plans to cut the budget deficit but by April that year falls in the equity market, along with an agreement of terms for the IMF programs in May 2000, caused pressure in the currency markets. A new Indonesian Government was elected in August 2001, consistent with the stress date noted in the table.

Indonesian economic conditions were the primary source of exceedances in 2002; including the announcement of the removal of petrol subsidies on January 24, 2002 associated with a negative tail stress date, a worsening current account position and falling coal prices (Indonesia is one of the world's largest producers of coal). The March 11, 2002 date corresponds to the beginning of talks to determine international borders with East Timor which gained formal independence on May 20.

Political uncertainty was dominant in 2004, with the Indonesian elections beginning in April and concluding in late September with the first democratically elected President. On October 4, 2004, one of the identified (negative) stress dates, the Governor of the Bank of Indonesia delivered a talk to the IMF highlighting these achievements and the improved outlook as Indonesia exited from the final IMF programs associated with the 1998 crisis; Boedino (2004).

The exogenous event of the tsunami which hit Indonesia on December 26, 2004 was felt in the currency markets in the first week of 2005 as a negative stress date. During 2005 the rupiah depreciated, and the Bank of Indonesia implemented a number of regulations designed to reduce volatility and speculative transactions; these included restrictions on derivatives, on rupiah trading with non-residents and expanding the instruments available for Bank of Indonesia intervention. On November 1, 2005 the Bank of Indonesia increased the BI interest rate by 125 basis points, but this was followed during the month by the release of further evidence of higher inflation (at an annual rate of 18.38% for headline inflation and 42.78% for administered prices including an increase in fuel prices) which corresponds with the identified stress date in the table. This was followed by further bans on margin trading of the rupiah, currency swap intervention and a tightening of the net open market position that banks can hold in foreign exchange. Consequently, in 2006 volume in the swap markets was reduced by almost one-third and volatility declined; Bank of Indonesia (2005,2006).

In the first half of 2006 the Indonesian rupiah appreciated along with most other Asian currencies as a result of uncertainty about the timing of the turning point in the US monetary policy cycle (ultimately the completion of the tightening cycle in May) and capital inflows in the first part of the year. May saw the first of the three credit rating agency upgrades of Indonesian debt.

By comparison the Indonesian rupiah has experienced relatively little stress associated with the global financial crisis, showing only one (positive) stress date on April 2, 2009, aligned with the G-20 meetings of finance ministers to discuss the global financial crisis.

4.3.4 Japan

There are only 5 stress dates indicated for the Japanese exchange rate, and they are generally not signed (that is they do not associate with one tail but with a more general increase in volatility from both tails). In late 2008, concerns were expressed over the length of the recovery from crisis, expressed particularly in July and October that year, although October 7 also aligns with the ratification of the Troubled Assets Relief Program in the US. The election of a new Government in Japan, overcoming the ruling coalition and appointment of a new Prime Minister is associated with stress in September 2009. News of a worsening outlook for Japanese debt issued by Moody's aligns with the February 22, 2011 date. In early 2012 the yen suffered a substantial depreciation; the early February stress date noted here is consistent with the emerging pressure associated with the expansion of the Bank of Japan asset buying program.

4.3.5 Korea

The 15 stress days for Korea feature a cluster at the beginning of the sample associated with the transition from an exchange rate regime with a limited band to a more flexible regime in December 1997, part of the terms of an IMF relief package. Early in the sample there are consequently a number of stress dates indicating that the fixed exchange rate regime was under pressure, and the existing stress associated with adjusting to the new regime in early 1998.

Korea implemented significant restructuring of its financial sector in 2001. The year was punctuated by drops in the KOPSI sufficient to prompt support from the Government, including its largest one-day drop on September 12, 2001 following the terrorist attacks in the US. Throughout this year Government reforms included the liquidation of some financial institutions and recapitalization funding. Coupled with the dot-com crisis in the US, these reforms are likely to be associated with the stress dates detected in that year and into early 2002; BOK (2002). The October 2005 negative stress date is associated with a short-lived appreciation in the won, beginning around October 14, and ending abruptly almost a fortnight later, accompanied at the time by concerns about intervention by the Bank of Korea. The stress date on 27 May 2008 corresponds to the announcement of Asian central bank interventions to support depreciating local currencies.

4.3.6 Malaysia

Malaysia experiences very few of its 26 stress dates in the first half of the sample. A small cluster appears in the second half of 1999 and early 2000. In July 2005 Malaysia returned to a managed float exchange rate regime. Initially, the central bank intervened frequently to maintain a stable exchange rate (Aziz 2013) and this corresponds with multiple stress negative tail dates during this period. Aziz (2013) records that Bank Negara intervention activity subsequently decreased, but was extensive during 2007-2008. Intervention was sufficient to increase international reserves by 50 percent between January 2007 and June 2008, and subsequently to reduce them by $US32 billion between September 2008 and April 2009. As with other Asian economies, Malaysia experienced strong capital investment outflow during 2008 as a consequence of the global financial conditions.

The stress date on October 29, 2008 is likely to be related to the general crash in Asian stock markets on that day, with the Hong Kong market falling by 12 percent and the Nikkei reaching a 20 year low. This followed the events in Europe over previous weeks which saw a significant number of countries appeal to the IMF for emergency aid, and was associated with a dramatic global loss of confidence. In the first months of 2013 the Malaysian ringgit exhibited some upward (positive and general) stress, as it appreciated against the US dollar.

4.3.7 Singapore

In Singapore, 10 dates are identified as exceeding the 4 standard deviation threshold. Throughout 1997 and 1998 the events identified are associated with the Asian financial crisis, and reflect the changing status of Singaporean assets to more aligned with regional problems during that period. From 1999 US economic conditions were responsible for most instances of pressure, and this feature prevailed until late 2010. From that period the US effects were punctuated by instances of Singaporean based news - particularly the varying expectations for Singaporean growth.

4.3.8 Thailand

Of the 19 stress days identified for Thailand, most occur between 1996 and 1998. Thailand transitted from a fixed exchange rate regime to a more flexible regime during the 1997-1998 Asian crisis period; with the date of the float of the Thai baht on July 2, 1997 often given as the starting point for the crisis. Unsurprisingly the Thai baht exhibits many stress dates in the period leading up to the crisis and during its course, many of these dates are evident in the negative tails or across both tails. The IMF programs for Thailand underwent 9 different negotiations between August 1997 and September 1999, and the uncertainty around these changing plans contributed to stress in the currency during this period; Goldstein et al (2003) provide a review of the extent of the IMF conditionality and structural reforms requested for Thailand, Indonesia and Korea.

From 2003 to 2006 there is one stress date indicated in each year. The September 2006 positive stress date reflects uncertainty corresponding to the aftermath of the coup on September 19. Pressure on the baht that year ultimately led to the imposition of short-term capital flow restrictions in Thailand from December. In June and July 2008 the Thai stock market experienced an outflow of international investors, partly in response to the worsening international situation and general flight to quality. By July 2009 the economic recovery was slowing, with a contracting export sector (somewhat offset by lower oil prices) and continued deflationary pressures.

5 Conclusion

The features of the high frequency financial data are important in pricing derivative products, hedging and volatility forecasting. While there is evidence for liquid, developed markets that these data are consistent with the presence of jumps and Brownian motion, this paper is the first to contribute formal evidence for Brownian motion and jumps in the exchange rates for emerging Asian markets against the US dollar. The evidence for infinite activity in the jump process in these currencies is mixed.

The paper examines the exchange rates for eight Asian currencies against the US dollar – Australian dollar, Indian rupee, Indonesian rupiah, Japanese yen, Korean won, Malaysian ringgit, Singaporean dollar and Thai baht – over the period 1996 to 2013. The sample period allows us to determine whether the evidence for the composition of the data generating process changes between periods of calm and stress. We find that although the evidence for Brownian motion (and infinite activity jumps) does not change, the ability to differentiate jumps from noise is improved during periods of stress. Taking advantage of this characteristic, we develop an index to detect the emergence of stressful periods in the markets. The stress index compares the jump characteristics of tail returns over consecutive periods to obtain a measure of the extent of change; when this change exceeds a pre-determined threshold we identify a stressful day for the currency in question. This approach adopts some of the methodologies for determining stress thresholds from the widely used exchange market pressure index pioneered by Eichengreen et al (1996), but has the advantage of not requiring ad hoc truncation choices to differentiate stress dates.

Using central bank and IMF reports we successfully align the stress dates identified for each currency with the economic conditions and events of the period. In general, the currencies experiencing the fewest stress days are those with the greatest global volume according to the BIS (2013) triennial survey of foreign exchange activity. Emerging markets typically experience more stress days, although India is a particular exception. The massive growth in volume of trade in the Indian rupee over the sample period may be a contributing factor – but does not mask all internal stressful events. Significant political events, such as coups or uncertainty about future governments are evident in the currency stress days identified. There is no readily apparent relationship between the numbers of stress days and exchange rate regime, although a clustering of stress dates relates to intervention measures taken to calm volatility in the Malaysian ringitt after the currency was refloated, and others are associated with the implementation of regulatory policies to reduce (speculative) derivative trading in Indonesia. In general, currencies showed higher sensitivity to local announcements than to relevant international news.

In summary, we provide evidence on the high frequency characteristics of the exchange rates for a number of currencies for emerging and developed Asian markets, and show how changes in these characteristics can be used to detect periods of stress in these markets. As a result we anticipate that incorporating high frequency stress signalling with conventional macroeconomic based indicators may improve the performance of early warning indicators; this is the focus of future work.

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Table 1: Aït-Sahalia and Jacod test statistics for exchange rates against the US dollar: 1996-2013: non-standardized, no truncation

Statistic	Australia	India	Indonesia	Japan	Korea	Malaysia	Singapore	Thailand
				Mean				
S_J	1.4174	1.1682	1.0999	1.5239	1.1562	22.3771	1.1363	0.8857
S_W	1.4654	1.3999	1.3284	1.4995	1.4559	1.3774	1.5015	1.3949
S_{FA}	1.3880	1.0358	0.9402	1.4814	1.2284	0.9973	1.0792	0.8463
S_{TI}	1.7296	1.1722	1.1034	1.8502	1.1701	22.4010	1.3075	0.8993
S_{TI}^+	1.8992	1.2443	1.0643	2.0205	3.5823	73.5752	1.3699	0.9131
S_{TI}^-	1.9038	1.8792	1.2528	2.0287	1.2419	3.4144	1.3658	0.9236
				Median				
S_J	1.3003	1.0000	0.9998	1.3540	1.0028	1.0000	1.0000	0.8763
S_W	1.4583	1.3639	1.2904	1.4871	1.4041	1.3600	1.4939	1.3549
S_{FA}	1.2848	0.9835	0.8631	1.3351	1.0523	0.9113	0.9823	0.8201
S_{TI}	1.4966	1.0001	1.0000	1.5873	1.0036	1.0000	1.0762	0.8826
S_{TI}^+	1.4859	1.0000	0.9914	1.5763	1.0021	1.0000	1.0233	0.8698
S_{TI}^-	1.4642	1.0000	0.9978	1.5715	1.0002	1.0000	1.0356	0.8755
				Standard deviation				
S_J	0.6836	7.6989	0.7576	0.8186	0.6663	1226.6481	1.9394	0.7072
S_W	0.1129	0.2286	0.2693	0.1374	0.8168	0.2686	0.1794	0.5892
S_{FA}	0.7023	0.6609	2.5701	0.7947	1.0538	0.8408	0.7035	0.4693
S_{TI}	1.0826	7.7938	0.7662	1.1477	0.6878	1226.6483	2.0798	0.9273
S_{TI}^+	1.5793	9.7983	0.8664	1.6465	148.0897	4235.7537	2.3388	0.7168
S_{TI}^-	1.6084	26.7742	3.7077	1.6414	0.8937	105.0072	2.7585	1.2011
				Kurtosis				
S_J	6.00	4359.58	45.38	32.46	99.71	3622.43	1999.46	1267.27
S_W	1.08	38.87	43.58	571.13	3276.80	392.87	3.68	1704.87
S_{FA}	25.42	375.17	3603.24	32.83	594.82	501.66	386.66	246.97
S_{TI}	40.93	4361.21	44.22	27.52	89.42	3622.43	1705.66	2202.61
S_{TI}^+	17.31	3647.93	119.26	17.94	4320.10	3546.23	2105.55	82.39
S_{TI}^-	24.47	3144.48	3486.97	15.95	24.22	3484.83	3231.47	1882.34
N	1294272	1294272	1293984	1294272	1293408	1293696	1294272	1294272

Table 2: Aït-Sahalia and Jacod test statistics for exchange rates against the US dollar: 1996-2013: non-standardized, outliers greater than 10 removed

Statistic	Australia	India	Indonesia	Japan	Korea	Malaysia	Singapore	Thailand
				Mean				
S_J	1.4174	1.0390	1.0945	1.5205	1.1499	1.1647	1.0977	0.8780
S_W	1.4654	1.3999	1.3284	1.4995	1.4438	1.3742	1.5015	1.3826
S_{FA}	1.3856	1.0281	0.8876	1.4782	1.2083	0.9813	1.0703	0.8406
S_{TI}	1.7210	1.0415	1.0979	1.8404	1.1638	1.1764	1.2674	0.8877
S_{TI}^{+}	1.8560	1.0544	1.0590	1.9618	1.2921	1.1261	1.3026	0.9052
S_{TI}^{-}	1.8458	1.1084	1.1877	1.9697	1.2386	1.1548	1.3218	0.8998
				Median				
S_J	1.3003	1.0000	0.9998	1.3540	1.0027	1.0000	1.0000	0.8763
S_W	1.4583	1.3639	1.2904	1.4871	1.4040	1.3600	1.4939	1.3548
S_{FA}	1.2847	0.9832	0.8623	1.3350	1.0511	0.9111	0.9823	0.8199
S_{TI}	1.4957	1.0001	1.0000	1.5861	1.0036	1.0000	1.0758	0.8826
S_{TI}^{+}	1.4814	1.0000	0.9914	1.5698	1.0019	1.0000	1.0220	0.8686
S_{TI}^{-}	1.4573	1.0000	0.9977	1.5632	1.0002	1.0000	1.0353	0.8750
				Standard deviation				
S_J	0.6836	0.4646	0.7120	0.7863	0.5972	0.9332	0.5940	0.4843
S_W	0.1129	0.2286	0.2693	0.1374	0.2615	0.2121	0.1794	0.2625
S_{FA}	0.6839	0.5369	0.4403	0.7663	0.7478	0.5742	0.5550	0.3836
S_{TI}	1.0172	0.4722	0.7207	1.0780	0.6208	0.9484	0.8135	0.5073
S_{TI}^{+}	1.4067	0.5748	0.7951	1.4184	0.9265	0.9128	1.0135	0.6443
S_{TI}^{-}	1.3712	0.7071	1.0043	1.4274	0.8674	0.9802	1.0282	0.6031
				Kurtosis				
S_J	6.00	55.66	14.87	6.80	23.13	24.57	9.99	17.44
S_W	1.08	38.87	43.58	571.13	111.65	13.43	3.68	260.81
S_{FA}	15.21	17.46	36.67	12.76	8.35	44.09	18.37	7.13
S_{TI}	4.42	55.25	14.88	3.24	21.75	23.07	12.02	16.62
S_{TI}^{+}	4.49	43.62	16.34	3.35	9.78	18.02	6.40	26.64
S_{TI}^{-}	4.74	23.89	11.97	3.01	11.19	18.44	7.87	18.92
N	1294272	1294272	1293984	1294272	1293408	1293696	1294272	1294272

Table 3: Standardized t-statistics for exchange rates against the US dollar: average for sample period

Statistic	Australia	India	Indonesia	Japan	Korea	Malaysia	Singapore	Thailand
				no truncation				
$\widehat{S_J}$	-0.7419	-0.5353	-0.7974	-0.6239	-0.5881	13.7154	-1.2082	-1.3002
$\widehat{S_W}$	0.6898	-0.0860	-0.4439	1.0997	0.2441	-0.1728	1.1806	-0.1158
$\widehat{S_{FA}}$	-2.1314	-1.7751	-1.6029	-1.8966	-1.4010	-1.1582	-2.8700	-2.4682
				outliers larger than 10 removed				
$\widehat{S_J}$	-0.7419	-0.7151	-0.8021	-0.6283	-0.5936	-0.7450	-1.2533	-1.3176
$\widehat{S_W}$	0.6898	-0.0860	-0.4439	1.0997	0.2060	-0.1783	1.1806	-0.1410
$\widehat{S_{FA}}$	-2.1404	-1.7751	-1.6917	-1.9077	-1.4316	-1.1735	-2.8922	-2.4755

Table 4: Aït-Sahalia and Jacod statistics for calm sub-periods: selected as lowest 90 day moving average RV in each sample

Statistic		Australia	India	Indonesia	Japan	
	Start	26-Jul-96	16-Apr-97	24-Sep-96	4-Jul-12	
	End	28-Nov-96	19-Aug-97	27-Jan-97	6-Nov-12	
S_J	Mean	1.1442	1.0091	0.9227	1.3693	
	Median	1.0845	0.9998	0.9884	1.2304	
	Skew	0.7090	0.0152	0.6808	1.0932	
	Kurtosis	0.5085	7.6951	2.7610	1.3138	
S_W	Mean	1.4193	1.4541	1.2016	1.5973	
	Median	1.4063	1.4011	1.1839	1.5785	
	Skew	1.0035	0.7907	0.7501	0.4918	
	Kurtosis	6.6588	0.1512	1.3177	-0.4558	
S_{FA}	Mean	1.1063	0.9595	0.8549	1.3303	
	Median	1.0540	0.8918	0.8495	1.1813	
	Skew	0.6662	2.2011	0.3561	1.1232	
	Kurtosis	0.1794	6.8492	1.2435	1.5116	
		Korea	Malaysia	Singapore	Thailand[a]	Thailand[b]
	Start	26-Jan-96	23-Aug-05	28-Aug-96	09-Sep-96	29-Oct-03
	End	7-Jun-96	3-Jan-06	31-Dec-96	10-Jan-97	02-Mar-04
S_J	Mean	1.3375	0.9113	0.9345	0.9678	0.8370
	Median	1.0000	0.9473	0.8912	0.9899	0.8879
	Skew	1.8582	1.7440	1.0815	1.8475	0.4553
	Kurtosis	3.3914	5.4564	1.9454	9.2329	1.9133
S_W	Mean	1.4619	1.3396	1.3675	1.2353	1.2505
	Median	1.4167	1.3204	1.3569	1.2093	1.2194
	Skew	0.8949	0.9949	0.8381	0.9267	3.2633
	Kurtosis	0.7179	1.0978	2.1580	1.6806	17.1642
S_{FA}	Mean	1.0404	0.7805	0.8280	0.8650	0.8336
	Median	0.8542	0.7717	0.7968	0.8879	0.8187
	Skew	3.4098	1.2715	1.4393	0.9758	-0.0069
	Kurtosis	17.5401	5.9048	4.4479	4.1404	-0.1863

[a]Selection of the calmest sample includes the pre-float period.
[b]Selection of the calmest sample excludes the pre-float period.

Table 5: Aït-Sahalia and Jacod statistics for the most volatile sub-periods:selected as highest 90 day moving average RV in each sample (excluding outliers greater than 10)

Statistic		Australia	India	Indonesia	Japan
	Start	6-Oct-08	18-Sep-08	31-Aug-10	10-Sep-98
	End	6-Feb-09	21-Jan-09	3-Jan-11	13-Jan-99
S_J	Mean	1.6857	1.2950	1.1634	1.4800
	Median	1.5992	1.0008	1.0053	1.3858
	Skew	0.8873	3.8234	4.3935	1.0052
	Kurtosis	1.2695	14.5242	23.3648	2.7938
S_W	Mean	1.4185	1.3387	1.3259	1.4242
	Median	1.4042	1.3427	1.3258	1.4071
	Skew	0.3840	1.0179	0.3594	0.8070
	Kurtosis	-0.2991	8.8455	1.3596	0.8820
S_{FA}	Mean	1.6318	1.1969	0.9631	1.4675
	Median	1.5685	1.1167	1.0000	1.3376
	Skew	0.8346	4.6590	-0.0795	1.7729
	Kurtosis	1.3344	33.7161	0.5715	5.8538
		Korea	Malaysia	Singapore	Thailand
	Start	20-Nov-97	7-Jan-98	13-Jul-98	26-Jun-07
	End	25-Mar-98	12-May-98	17-Nov-98	29-Oct-07
S_J	Mean	1.2589	0.9373	0.8468	0.7849
	Median	1.0053	0.8124	0.9228	0.7949
	Skew	2.7892	2.2934	0.8036	-0.5324
	Kurtosis	11.4691	8.6842	1.9498	-0.5975
S_W	Mean	1.4632	1.4257	1.3655	2.0445 (1.4324)
	Median	1.4278	1.4168	1.3599	1.2933 (1.2813)
	Skew	0.6572	0.8365	0.9514	6.7472 (2.4570)
	Kurtosis	0.4184	1.7866	3.4392	49.4623 (8.3667)
S_{FA}	Mean	1.6553 (1.0049)	0.9034	0.8846	0.7456
	Median	0.9239 (0.9175)	0.7970	0.8999	0.7726
	Skew	7.8856 (2.0817)	1.9630	0.3697	0.1344
	Kurtosis	66.1589 (6.9100)	6.3221	0.5041	3.6399

Table 6: Aït-Sahalia and Jacod statistics for the further periods of stress identified using RV (excluding outliers greater than 10)

Statistic		India			
	Start	15-Mar-96	18-Nov-97	31-Aug-10	17-Aug-11
	End	25-Jul-96	23-Mar-98	3-Jan-11	20-Dec-11
S_J	Mean	1.0846	1.1016	1.1634	1.1479
	Median	1.0000	1.0008	1.0053	1.0024
	Skew	3.3274	3.7104	4.3935	6.9393
	Kurtosis	15.7301	22.2699	23.3648	55.3448
S_W	Mean	1.4400	1.3823	1.3259	1.3360
	Median	1.4232	1.3591	1.3258	1.2945
	Skew	0.4339	0.0069	0.3594	3.8864
	Kurtosis	0.7972	2.2525	1.3596	25.1220
S_{FA}	Mean	0.9927	0.9999	0.9631	1.1983
	Median	0.9189	0.9989	1.0000	1.1215
	Skew	2.3843	1.6337	-0.0795	2.4086
	Kurtosis	9.2976	4.5038	0.5715	13.3224
		Indonesia			
	Start	13-May-98	26-Nov-98	20-Jul-01	21-Oct-08
	End	18-Sep-98	1-Apr-99	22-Nov-01	23-Feb-09
S_J	Mean	0.7707	0.8673	1.0497	0.9908
	Median	0.8005	0.8272	0.9826	1.0000
	Skew	0.7214	2.0431	2.1821	0.9805
	Kurtosis	3.6987	8.9441	7.2915	7.5264
S_W	Mean	1.3138	1.3570	1.3898	1.2645
	Median	1.2819	1.3499	1.3782	1.2102
	Skew	0.6536	0.8455	0.5108	1.4527
	Kurtosis	0.9367	2.4128	0.3784	2.3585
S_{FA}	Mean	0.7962	0.7905	1.0230 (0.8738)	0.8691
	Median	0.8278	0.8042	0.7959 (0.7907)	0.9727
	Skew	0.2380	0.5424	7.7376 (1.5752)	0.1196
	Kurtosis	0.6390	1.7838	66.8680 (4.0584)	1.7805

Table 7: Aït-Sahalia and Jacod statistics for the further periods of stress identified using RV (excluding outliers greater than 10)

Statistic		Australia		Japan	Korea	
	Start	9-Jun-98	13-Feb-01	8-Sep-08	4-Mar-02	3-Sep-08
	End	15-Oct-98	18-Jun-01	9-Jan-09	5-Jul-02	6-Jan-09
S_J	Mean	1.4401	1.3514	1.4983	1.0008	1.2091
	Median	1.2482	1.2019	1.3963	1.0000	1.0084
	Skew	2.3372	3.0500	1.5475	1.3623	3.2335
	Kurtosis	8.7125	17.6802	4.3020	29.3264	10.9540
S_W	Mean	1.3668	1.3756	1.4591	1.3611	1.4392
	Median	1.3633	1.3699	1.4445	1.1974	1.3960
	Skew	0.5630	0.5428	0.6119	2.2459	1.0484
	Kurtosis	0.2550	0.4295	0.4428	6.6041	1.0106
S_{FA}	Mean	1.2791	1.2859	1.6342 (1.4773)	1.4222	1.2135
	Median	1.2098	1.2290	1.3764 (1.3692)	1.0000	1.1044
	Skew	0.5442	0.4693	6.6987 (1.7566)	1.7882	1.5036
	Kurtosis	0.6089	0.0264	54.4218 (5.0507)	3.2923	3.1692

		Malaysia	Singapore		Thailand
	Start	7-Jul-11	8-Sep-08	5-Aug-11	30-May-97
	End	9-Nov-11	9-Jan-09	8-Dec-11	07-Oct-97
S_J	Mean	1.6801 (1.1792)	1.3648	1.4318	0.7686
	Median	1.0000 (1.0000)	1.2739	1.3717	0.7317
	Skew	6.3621 (1.7808)	1.1848	2.1357	0.6207
	Kurtosis	43.1688 (3.1885)	2.6604	9.3919	1.8087
S_W	Mean	1.4442	1.4701	1.5386	1.4061
	Median	1.4071	1.4762	1.5295	1.3705
	Skew	1.1635	0.4613	0.7350	0.1518
	Kurtosis	1.4805	1.8340	1.7436	0.9114
S_{FA}	Mean	0.9941	1.3381	1.4402	0.7437
	Median	0.9034	1.2739	1.3529	0.6932
	Skew	1.3499	0.5567	3.7447	0.5227
	Kurtosis	3.7679	0.3977	23.8646	0.9551

Table 8: Number and proportion of days above threshold value for stress index for January 1996 to March 2013

Days	Australia	India	Indonesia	Japan	Korea	Malaysia	Singapore	Thailand
	Stress Days with all data included in calculation of threshold σ							
Above σ	9	19	27	26	19	6	31	31
(%)	0.20	0.44	0.62	0.58	0.43	0.17	0.69	0.69
Above 2σ	5	9	18	8	15	4	21	18
(%)	0.11	0.21	0.41	0.18	0.34	0.11	0.47	0.40
Above 3σ	2	6	12	6	13	3	13	14
(%)	0.04	0.14	0.27	0.13	0.30	0.08	0.29	0.31
Above 4σ	2	5	9	5	10	2	10	13
(%)	0.04	0.11	0.21	0.11	0.23	0.06	0.22	0.29
	Stress Days with outliers excluded in calculation of threshold σ							
Above σ	59	19	46	26	26	52	31	46
(%)	1.31	0.44	1.05	0.58	0.59	1.43	0.69	1.03
Above 2σ	23	9	25	8	16	35	21	29
(%)	0.51	0.21	0.57	0.18	0.36	0.97	0.47	0.65
Above 3σ	16	6	22	6	13	28	13	22
(%)	0.36	0.14	0.50	0.13	0.30	0.77	0.29	0.49
Above 4σ	10	5	17	5	13	24	10	16
(%)	0.22	0.11	0.39	0.11	0.30	0.66	0.22	0.36
	Stress Days identified with either calculation of threshold σ							
Above σ	60	19	47	26	28	58	31	49
(%)	1.34	0.44	1.08	0.58	0.64	1.60	0.69	1.09
Above 2σ	24	9	26	8	18	39	21	32
(%)	0.53	0.21	0.60	0.18	0.41	1.08	0.47	0.71
Above 3σ	17	6	23	6	15	31	13	25
(%)	0.38	0.14	0.53	0.13	0.34	0.85	0.29	0.56
Above 4σ	11	5	18	5	15	26	10	19
(%)	0.24	0.11	0.41	0.11	0.34	0.72	0.22	0.42
Total days	4,493	4,365	4,364	4,493	4,390	3,626	4,489	4,485

Table 9: Share and rank of sample currencies global exchange market turnover

Currency	1998		2001		2004		2007		2010		2013	
	Share	Rank	Share %	Rank	Share %	Rank	Share %	Rank	Share %	Rank	Share %	Rank
US	86.8	1	89.9	1	88.0	1	85.6	1	84.9	1	87.0	1
Japan	21.7	2	23.5	3	20.8	3	17.2	3	19.0	3	23.0	3
Australia	3.0	6	4.3	7	6.0	6	6.6	6	7.6	5	8.6	5
Singapore	1.1	7	1.1	12	0.9	14	1.2	13	1.4	12	1.4	15
Korea	0.2	18	0.8	15	1.1	11	1.2	14	1.5	11	1.2	17
India	0.1	22	0.2	21	0.3	20	0.7	19	1.0	15	1.0	20
Malaysia	0.0	27	0.1	26	0.1	30	0.1	28	0.3	25	0.4	25
Thailand	0.1	19	0.2	24	0.2	22	0.2	25	0.2	26	0.3	27
Indonesia	0.1	25	0.0	28	0.1	27	0.1	29	0.2	30	0.2	30

Adjusted for local and cross-border inter-dealer double-counting. As two currencies are involved in each transactions total volumes total to 200% rather than 100%. Source: BIS (2013) Table 2.

Table 10: Days with $S_{i,t}$ exceeding 3 standard deviations over the median

	Australia	India	Indonesia	Japan	Korea	Malaysia	Singapore	Thailand
1996	10-Jan * 3-Sep *	15-Feb	16-Apr $^{-4}$ 10-Jun * 18-Oct ^{4*}		20-Mar $^{+/-4}$ 20-Sep ^{4**} 23-Dec $^{-4*}$			24-Jan $^{+4*}$ 9-Feb $^{+/-4}$ 24-Jul * 23-Sep $^{-4**}$
1997							6-May $^{-4}$ 3-Jul	21-Feb $^{+/-4*}$
1998	28-Aug $^{+4*}$		3-Mar * 29-May $^{+/-4}$ 30-Dec $^{+/-4}$		26-Jan $^{-4}$		19-Mar $^{-4}$ 1-Jun $^{+4}$ 25-Jun ^{4} 17-Nov	10-Feb $^{-4*}$ 12-Mar $^{+/-4*}$ 26-Mar * 30-Apr $^{+/-4}$ 3-Jun * 22-Jul $^{-4}$ 21-Sep $^{-4}$ 7-Oct $^{-4}$ 17-Dec $^{-4**}$
1999	11-Mar ^{4*} 3-May $^{+4*}$	21-Jun $^{-4}$	2-Dec $^{+4*}$ 8-Dec $^{-4}$		17-Nov $^{-4}$	27-Jul $^{+4*}$ 30-Nov $^{-4*}$	22-Jul $^{+4}$ 3-Nov $^{+4}$	9-Mar $^{-4**}$ 6-Apr *
2000	17-Mar ^{4*} 7-Dec ^{4*}	11-Aug $^{-4}$	21-Jun $^{+4*}$		30-May ^{4} 28-Aug $^{-4*}$ 25-Oct ^{4*}	11-Jan ^{4*}	14-Mar $^{-4}$	
2001	16-Apr ^{4**} 29-May $^{+/-4}$ 5-Jul $^{-4*}$ 28-Dec *	10-Sep $^{+4}$	8-Aug $^{-4*}$ 14-Nov * 4-Dec *		10-Jan $^{-4}$ 3-Apr $^{+4}$ 16-Jul $^{-4*}$ 16-Oct $^{-4*}$		4-May $^{+4}$	
2002		21-Jan $^{-4}$	24-Jan $^{-4}$ 11-Mar ^{4} 13-Aug ^{4} 18-Sep $^{+4*}$		1-Feb $^{+4}$		14-Oct	
2003	1-Dec *			10-Dec ^{4}			16-Jan $^{+4}$ 22-Sep $^{-4}$	25-Jun $^{-4}$
2004			19-Jan $^{+4*}$ 4-Oct $^{-4*}$					7-Oct $^{+/-4}$
2005	29-Mar *		3-Jan $^{-4}$ 23-Nov ^{4**}		14-Oct $^{-4}$	22-Jul ^{4**} 22-Dec $^{-4*}$		7-Dec $^{-4*}$
2006			20-Apr ^{4*}			4-Jan ^{4*} 25-Jan $^{-4*}$ 24-Feb * 14-Mar $^{-4*}$ 10-May $^{-4*}$ 22-Sep *		22-Sep $^{+4}$
2007			28-Sep *			13-Feb ^{4*} 11-May * 18-May ^{4*} 29-Nov $^{-4*}$		
2008		21-Mar $^{-4}$		7-Oct ^{4}	27-May ^{4**}	11-Jul ^{4*} 29-Oct **		1-Jul $^{+4}$
2009			2-Apr $^{+4*}$	7-Sep $^{+4}$		30-Jan $^{+4*}$ 27-Feb $^{+4*}$ 4-Mar ^{4*} 19-Mar $^{-4*}$ 28-Apr $^{+4*}$ 22-May * 20-Aug $^{-4*}$ 28-Aug ^{4*}		31-Jul $^{-4*}$
2010	15-Jan ^{4*} 1-Jun ^{4*}							20-Sep *
2011	28-Apr ^{4*}			18-Jan 22-Feb $^{+/-4}$				27-Jun *
2012	28-Aug *			3-Feb ^{4}		25-Jan $^{-4*}$ 26-Nov $^{-4*}$		14-Sep ^{4}
2013						4-Jan $^{+4*}$ 29-Jan ^{4*} 5-Feb ^{4*} 8-Feb $^{+4*}$		

^{4} Days exceeding 4 standard deviations over the median + (-) indicates positive (negative) stress day

* Standard deviation was calculated by excluding the outliers (values bigger than 1000)

** Standard deviation was calculated considering all the data (including outliers)

When no star, days were selected with both criteria

Figure 1: Non-standardized SJ

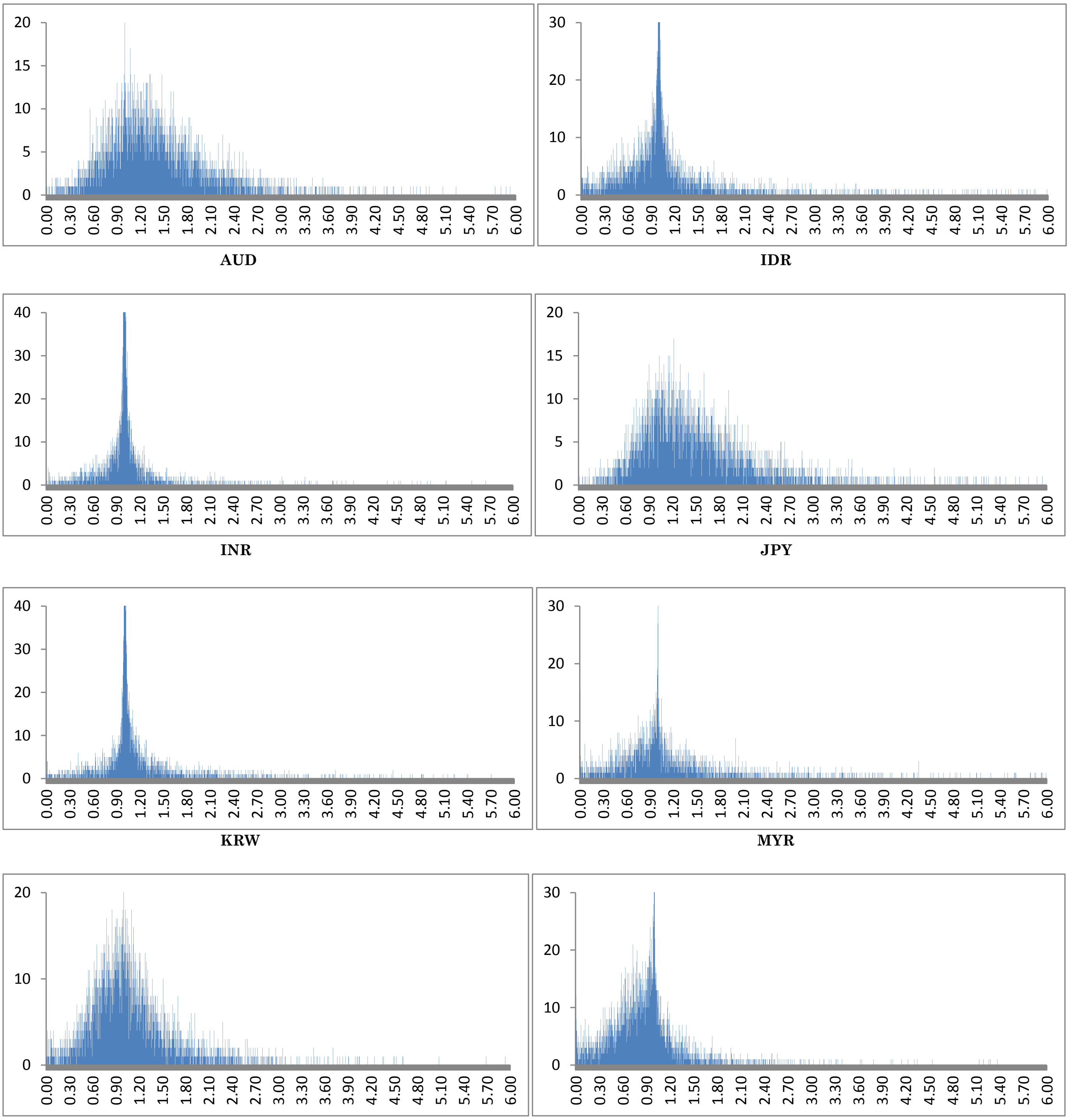


Figure 2: Non-standardized SW

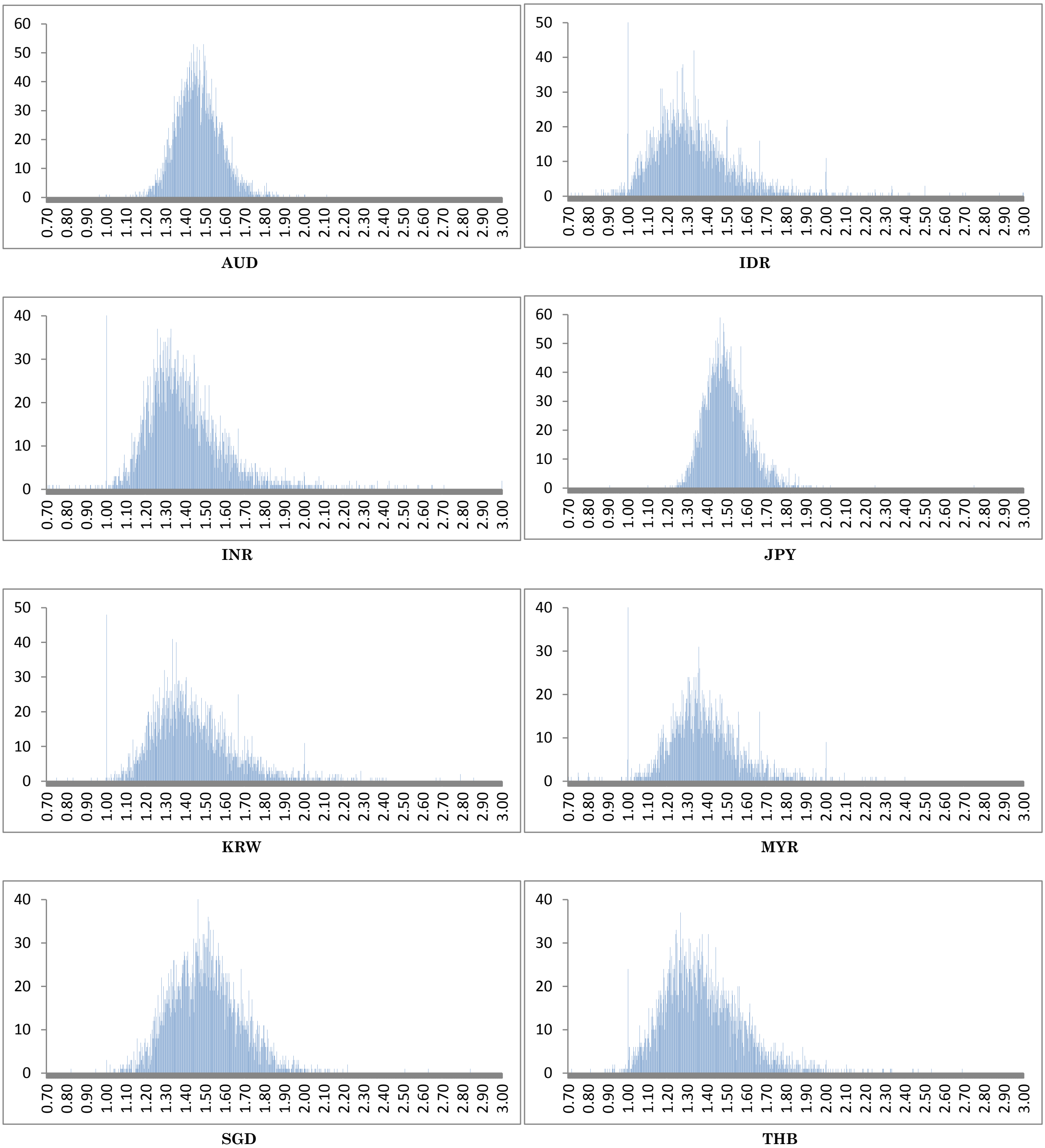


Figure 3: Non-standardized SFA

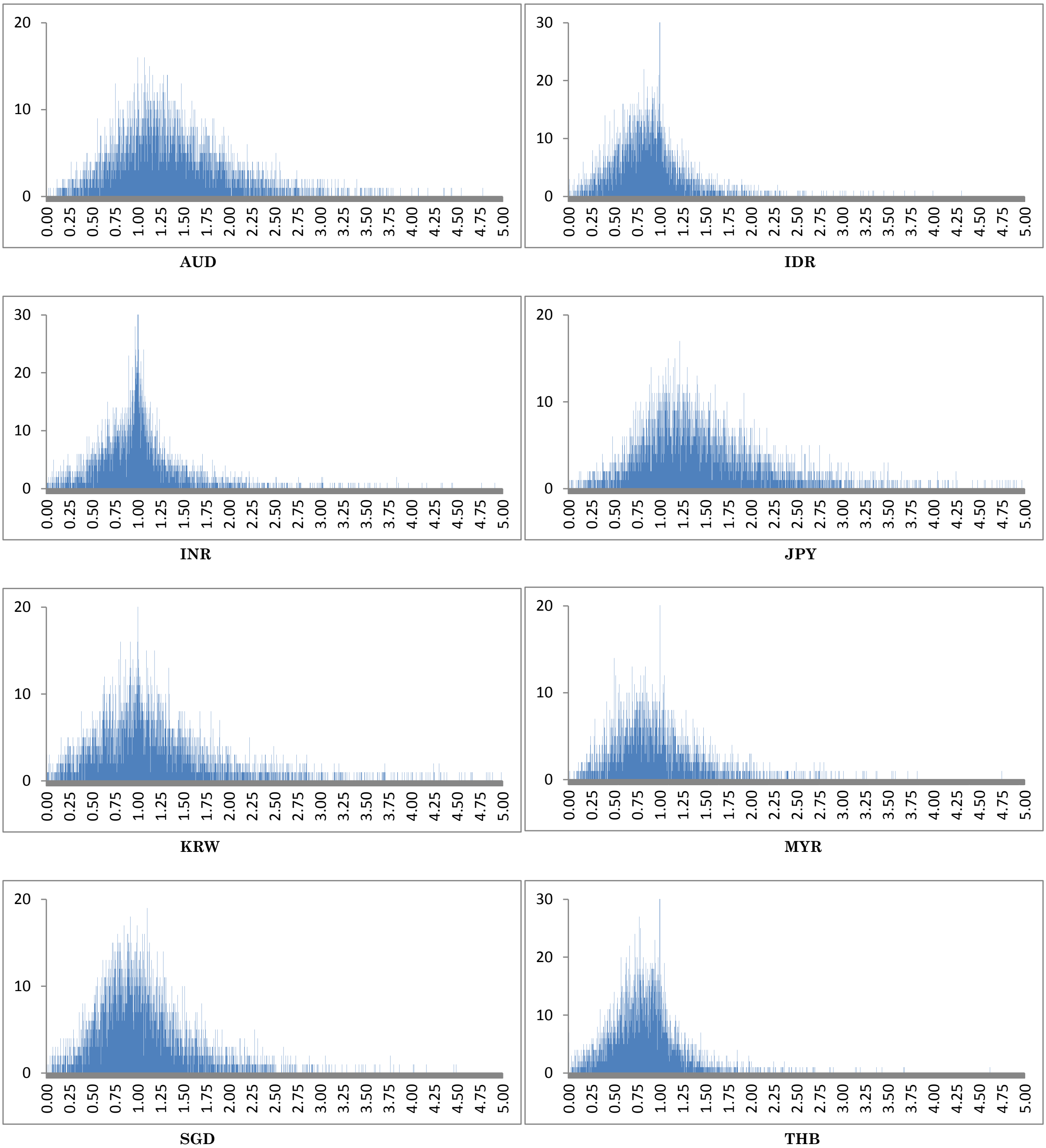


Figure 4: Non-standardized STI

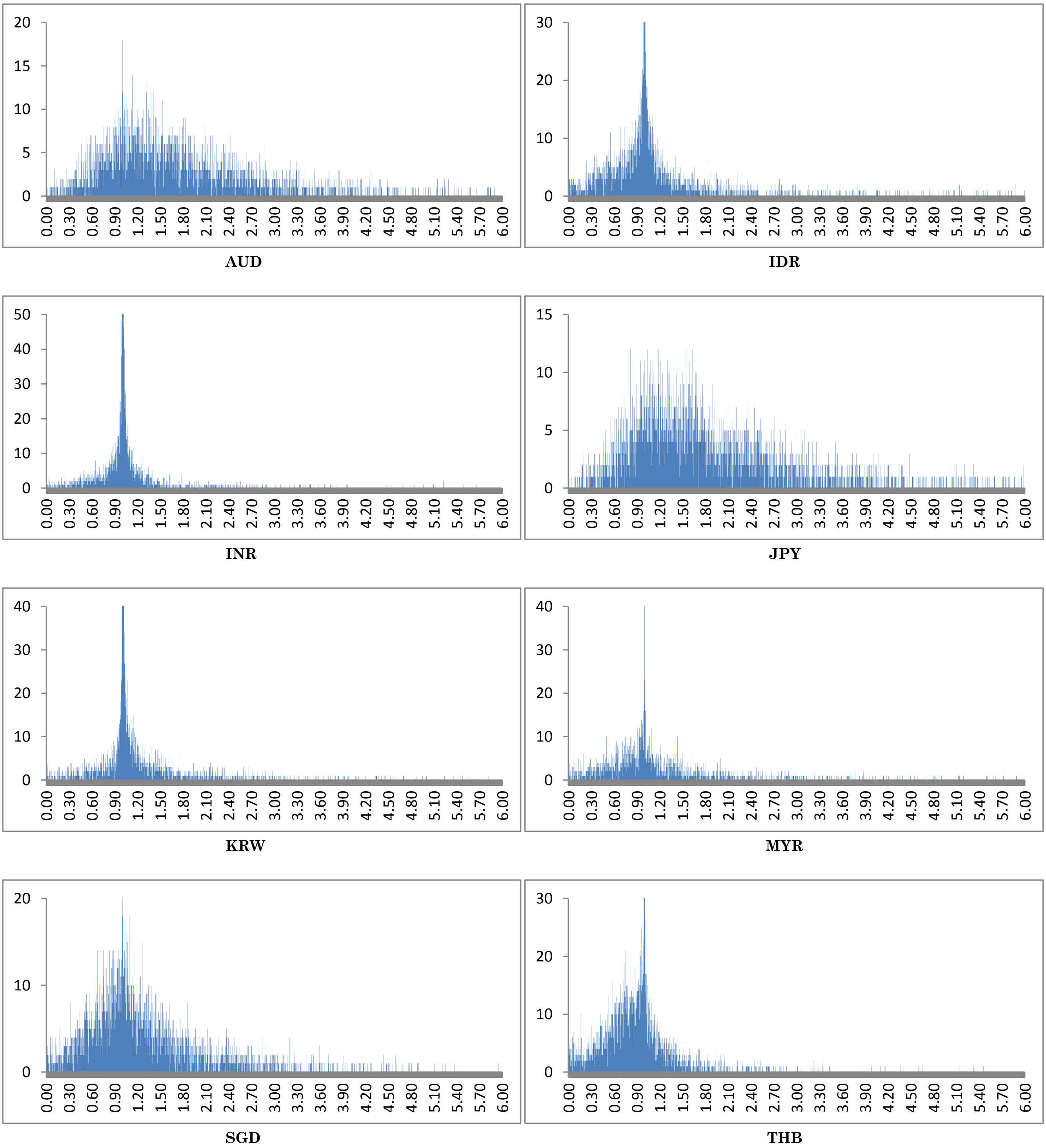
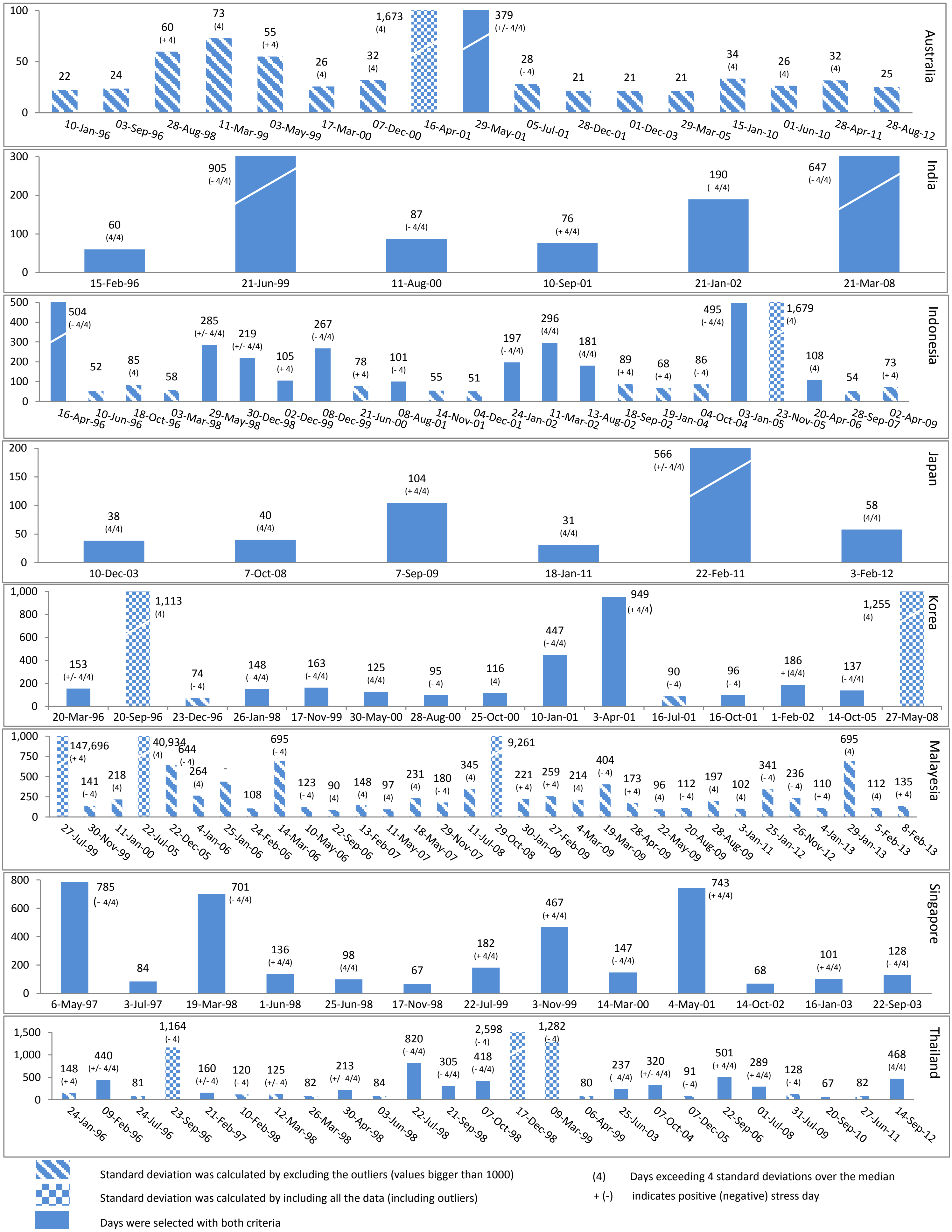


Figure 5: Days with Si,t exceeding 3 standard deviations over the median



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