The High Frequency Effects of Dollar Swap Lines*

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Abstract

We study the high frequency effects of dollar swap line announcements on asset prices. News about expanded dollar swap lines causes a reduction in liquidity premia, compression of deviations from covered interest parity (CIP), and depreciation of the dollar. Equity prices rise and the VIX falls, while the response of long-term government bond prices is mixed. These effects are qualitatively consistent with a general equilibrium model in which dollar swap lines increase the supply of safe dollar liquidity, and in which liquidity premia, CIP deviations, exchange rates, and other asset prices are jointly determined.

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1 Introduction

In recent crises, dollar swap lines between the U.S. Federal Reserve and foreign central banks have emerged as an integral part of the global policy response. In these arrangements, the Federal Reserve lends dollars to foreign central banks in exchange for foreign currency. For instance, in response to the Covid-19 pandemic, foreign central banks borrowed $450bn via swap lines by May 2020. This accounted for virtually all of the credit extended through liquidity facilities during the crisis, and nearly 20% of the entire increase in the Federal Reserve's balance sheet by that time.[1]

Assessing the effects of the dollar swap lines is challenging for two reasons. First, these tools are deployed precisely when the demand for dollars is high, making it difficult to separate the effects of demand shocks from policy-induced changes in supply. Second, these tools are deployed in concert with an array of other policy responses to crises such as conventional policy easing and quantitative easing programs, making it difficult to identify the effects of dollar swap lines alone.

In this paper, we provide high frequency estimates of the effects of dollar swap lines which can overcome these challenges and a framework to make sense of them. By focusing on tight intraday windows around dollar swap line announcements, we can plausibly identify shocks to the future supply of dollar liquidity alone. We find that news about expanded dollar swap lines causes a reduction in liquidity premia, compression of deviations from covered interest parity (CIP), and depreciation of the dollar. Equity prices rise and the VIX falls, while the response of long-term government bond prices is mixed. We focus on announcements during March 2020 but find that our results are robust to announcements during the September-October 2008 period as well. We then demonstrate that these effects are qualitatively consistent with a general equilibrium model in which liquidity premia, CIP deviations, exchange rates, and other asset prices are jointly determined. Dollar swap lines increase the supply of safe dollar liquidity to foreigners, compressing the liquidity premium. This in turn reduces foreigners' demand for hedging, compressing the CIP deviation, and revalues wealth in foreigners' favor, depreciating the dollar. Dollar equity prices rise because foreigners' financing cost falls, and the support to equity prices in bad future states lowers the VIX. Treasury bonds exhibit a more muted response than equities to the extent they provide liquidity services, the value of which has fallen.

[1] See `https://www.federalreserve.gov/monetarypolicy/bst_recenttrends.htm`.

Our empirical methodology focuses on the intraday responses to selected dollar swap line announcements in a broad range of asset classes. We first assemble a list of all announcements pertaining to dollar swap lines by the Federal Reserve over the 2007-2010 and 2020-2021 periods. From these, we identify eight announcements which were not accompanied by simultaneous news regarding other policies such as other crisis policies or FOMC statements. We then estimate the change in spot, futures, and forward prices of interest rates, exchange rates, equities, and bonds in tight windows around these eight announcements, using minute-by-minute data. Since this intraday data is more complete for the 2020-2021 announcements, we focus in the main text on these two announcements: on March 19, 2020 the Federal Reserve announced it would create temporary swap lines with nine central banks beyond the five central banks with which it already had standing facilities; and on March 20, 2020, the Federal Reserve announced it would increase the frequency of standing swap line operations from weekly to daily. Within two weeks from these announcements, foreign central banks drew nearly $400bn on the swap lines.

We first estimate the responses of money markets to these announcements. We obtain close to zero responses of Fed funds rates from futures prices both for the current and three-month ahead contract, indicating that conventional policy rates were not expected to change because of the swap lines. We then estimate sharp declines in three-month Libor rates from futures prices. The nearest three-month Libor rate fell by a cumulative $12bp$ and the 12-month ahead three-month Libor rate fell by a cumulative $5bp$ (both annualized), with monotonically declining responses in between. All of these are statistically significantly different from zero at conventional levels. While these may reflect a decline in counterparty risk among financial institutions, our preferred interpretation is that this reflects a decline in the liquidity premium, given the daily comovement between the three-month Libor/Treasury bill spread and other measures of liquidity premia (which we do not measure intraday) such as the three-month AA nonfinancial commercial paper/Treasury bill spread and swapped G10 government bond/Treasury bill spread over this period.

We next estimate the responses of foreign exchange markets to these announcements. In spot markets, we estimate a sharp and statistically significant depreciation of the dollar, by $72bp$ versus G10 currencies and $117bp$ versus emerging market currencies. The dollar depreciation is broad-based, with the Japanese yen the only currency of 11 in our dataset which do not appreciate versus the dollar. The three-month for-

ward premium, the log difference in the three-month forward rate less the spot rate with both expressed in foreign currency per dollar, rises by a statistically significant $21bp$ versus G10 currencies (again annualized). This in turn compresses the synthetic cost of borrowing in dollars for foreigners, the foreign interbank rate plus forward premium, relative to the actual dollar interbank rate — i.e., the deviation from CIP. Indeed, for currencies with sufficiently frequent intraday quotes in three-month OIS rates, we estimate very close responses of the forward premium and CIP deviation, reflecting a negligible response of the OIS rate differential. Given an average annualized three-month CIP deviation of $82bp$ on March 18 prior to the announcements, a compression of the average CIP deviation by $21bp$ is economically meaningful.

We finally characterize the broader responses of equity and bond markets. We estimate a $151bp$ increase in the S&P 500 futures price and broad increase in foreign equity futures prices, and $415bp$ decline in the VIX futures price.[2] The latter effect is statistically significantly different from zero at all conventional levels. By contrast, long-term government bond futures prices rise on March 19 but fall on March 20, and the cumulative response is an order of magnitude smaller than for equities. We further note that our use of intraday data is essential to identify these effects: using the cumulative two-day change in these asset prices instead, the S&P 500 futures price fell by $486bp$, the 30-year Treasury bond futures price rose by $488bp$, and the dollar appreciated by $66bp$, consistent with the flight to safety during this period.

We then interpret these findings through the lens of a general equilibrium model in which liquidity premia, CIP deviations, exchange rates, and other asset prices are jointly determined. There are two countries, the U.S. and Foreign, with representative agents who trade their endowments of distinct goods with consumption home bias. We refer to assets paying in units of the U.S. (Foreign) consumption bundle as dollar-denominated (Foreign-denominated). In our benchmark model, agents trade four sets of assets: "safe dollar bonds" which provide non-pecuniary liquidity services (such as dollar reserves or Treasury bills); "other dollar bonds" which do not provide such liquidity services (such as dollar Libor); Foreign-denominated bonds which also do not provide liquidity services; and a forward contract to exchange the Foreign consumption bundle for the U.S. bundle. There are three key frictions: Foreign pays

[2]We obtain similar results using spot prices but focus on futures given their intraday liquidity and coverage for announcements outside market hours, as in 2008. Throughout the paper, when the settlement month or quarter is not specified, it means the contract with the nearest settlement.

a quadratic cost in its net position in dollar-denominated assets, capturing the costs of having unhedged exchange rate exposure; Foreign faces a borrowing constraint in dollar Libor; and the U.S. pays quadratic costs in its position in each asset, capturing balance sheet costs arising from regulatory requirements.

We first characterize portfolios and asset prices in the steady-state of this economy. The non-pecuniary value of safe dollar bonds will, in equilibrium, result in a lower yield on these assets versus others. Since Foreign receives non-pecuniary benefits from holding these assets but faces a cost of having an unhedged portfolio, it will seek to simultaneously borrow in other dollar bonds or sell dollars forward to minimize its unhedged exposure. Facing a binding constraint in the first case, it will indeed sell dollars forward. The U.S.' balance sheet costs means that it requires compensation to provide these hedging services, resulting in a positive forward premium. This in turn translates to a steady-state deviation from CIP.

In this environment, dollar swap lines generate effects on asset prices qualitatively consistent with those observed in the data. Dollar swap lines are modeled as a commitment by the U.S. to loan dollar reserves against Foreign-denominated bonds for a fee. They put a ceiling on the equilibrium liquidity premium since, if safe dollar assets offer a sufficiently low return, Foreign would simply hold Foreign bonds and swap them for dollar reserves for a fee, obtaining dollar liquidity with a higher net return. When this ceiling is binding, a more generous swap line — as via a lower fee — indeed induces Foreign to substitute away from safe dollar bonds and compresses the liquidity premium. Because this also reduces Foreign's unhedged dollar exposure, it reduces Foreign's need for hedging and thus compresses the CIP deviation. The reduced liquidity premium and hedging costs revalue wealth in Foreign's favor, depreciating the dollar exchange rate. Extending the model to feature an additional dollar-denominated asset (dollar equities) that Foreign owns but which does not provide liquidity services, the reduced hedging costs in Foreign induce a rise in this asset price as its financing cost falls. The related support to the price of equities in bad future states reduces ex-ante expected volatility, consistent with the decline in the VIX. Finally, to the extent longer-term Treasury bonds provide liquidity services substitutable with Treasury bills or reserves, the compression of the liquidity premium accounts for the muted response of longer-term Treasury bonds relative to equities.

Related literature Our analysis of dollar swap lines sits between two rapidly growing literatures: one on the liquidity premium of safe, dollar-denominated assets, and another on deviations from CIP.

From an empirical perspective, our contribution to these literatures is to identify the effects of a particular structural shock of interest on liquidity premia, CIP deviations, exchange rates, and other asset prices. Jiang, Krishnamurthy, and Lustig (2021) and Engel and Wu (2022) document that a lower Treasury liquidity premium is associated with a depreciation and expected appreciation of the dollar. Avdjiev, Du, Koch, and Shin (2019) document that a weaker dollar is associated with a compressed CIP deviation. In all three cases, these papers identify important unconditional comovements between these variables. Our analysis identifies a specific shock to the supply of dollar liquidity and thus liquidity premia, and traces out the resulting effects on other asset prices including exchange rates and CIP deviations. In this respect it builds on Krishnamurthy and Vissing-Jorgensen (2012), Nagel (2016), Krishnamurthy and Li (2022), and other papers which estimate the demand for money and near-money assets using shocks to supply. The innovation relative to these papers is to focus on dollar swap lines as opposed to Treasury supply, and to study the effects on asset prices beyond liquidity premia.

From a theoretical perspective, our contribution to these literatures is to outline a general equilibrium model which jointly determines liquidity premia and CIP deviations. Engel (2016), Bianchi, Bigio, and Engel (2022), Jiang, Krishnamurthy, and Lustig (2022), Devereux, Engel, and Wu (2023), and Kekre and Lenel (2023) study the effects of the demand for safe dollar assets on international portfolios and exchange rates. We trace out the consequences for CIP by adding a motive for foreign agents to hedge their dollar exposure from these assets, and a cost for U.S. agents in providing these hedging services. These in turn build on findings in the literature on CIP deviations that the demand for safe dollar assets has been accompanied by a demand to hedge dollar exposure (Du and Huber (2023)) and that regulatory constraints constrain the supply of currency hedging (Du, Tepper, and Verdelhan (2018b)). Jiang et al. (2021) propose a link between the foreign demand for safe dollar assets and CIP deviations on which we build. Relative to their analysis, we study dollar swap lines and the effects on exchange rates and other asset prices. The effect on exchange rates is in particular driven by the effect on relative wealth in our segmented markets framework, echoing the mechanism in Jiang et al. (2022).

Our paper is of course not the first to study dollar swap lines. Among other recent important contributions, Baba and Packer (2009a,b) demonstrate that swap line operations reduced CIP deviations in 2008; Bahaj and Reis (2022) demonstrate both theoretically and empirically in 2011 that swap lines put a ceiling on CIP deviations and raised the price of corporate bonds disproportionately held by banks with access to the swap lines; and Bahaj and Reis (2020), Cetorelli, Goldberg, and Ravazzolo (2020a,b), and Goldberg and Ravazzolo (2022) demonstrate that swap lines reduced CIP deviations and supported the U.S. corporate credit market in 2020. Our paper makes three contributions to this work. First, we look beyond CIP deviations and corporate bonds to also estimate the effects of these policies on liquidity premia, exchange rates, aggregate stock markets, and the yield curve. Second, and relatedly, we use intraday data to estimate the effects on our aggregate asset prices of interest, whereas the existing literature has used daily or lower frequency data, and has used cross-sectional variation across banks or countries to identify its effects of interest.[3] Third, we provide a conceptual framework relating swap lines and CIP deviations to dollar liquidity premia and the dollar exchange rate. This in turn builds on Bahaj and Reis (2022), who focus on the first two.

2 Effects of dollar swap lines

In this section we provide our main results on the intraday responses to dollar swap line announcements in a broad range of asset classes.

2.1 Dollar swap line announcements

We first identify the subset of swap line announcements by the Federal Reserve for our analysis. Over the 2007-2010 period, we begin with the set of 15 swap line announcements reported in Table 1 of Goldberg, Kennedy, and Miu (2011). Over the

[3]In doing so, our paper complements large literatures on the high frequency effects of other central bank policies including conventional monetary policy (Cook and Hahn (1989), Kuttner (2001), Cochrane and Piazzesi (2002), Gurkaynak, Sack, and Swanson (2005a,b), among other papers) and quantitative easing (Gagnon, Raskin, Remache, and Sack (2011), Krishnamurthy and Vissing-Jorgensen (2011), Swanson (2011), among other papers). Studying dollar swap lines as a distinct policy tool is interesting in part because they have accounted for a significant share of the balance sheet expansion of central banks in recent crises, and in part because they necessarily involve transactions with foreigners, unlike these other policies.

2020-2021 period, we survey all press releases on the Federal Reserve website and identify six announcements pertaining to swap lines. From this list of 21 announcements, we then identify eight satisfying two criteria: the announcement must not be accompanied by a simultaneous announcement regarding other policies, and the timestamp of the announcement must be provided on the Federal Reserve website. Appendix A summarizes the initial sample of 21 announcements and the eight which we study.

In the main text, we focus on the effects of the two announcements in the 2020-2021 period satisfying our selection criteria. These are the March 19, 2020 announcement that the Federal Reserve would create temporary swap lines with nine central banks beyond the five central banks with which it already had standing facilities,[4] and the March 20, 2020 announcement that the Federal Reserve would increase the frequency of standing swap line operations from weekly to daily. Figure 1 depicts the rise in swap line usage after these announcements as well as the reduction in three measures of liquidity premia: the spread between three-month AA nonfinancial commercial paper and Treasury bills, the spread between three-month swapped G10 government bonds and Treasury bills, and the spread between three-month Libor and Treasury bills, all annualized. The reduction in liquidity premia in the several weeks following these announcements suggests a causal effect of the swap lines, but it is also possible that the latent shock driving up these premia simply reversed on its own. The behavior of liquidity premia on or immediately following the announcements are also mixed, likely reflecting shocks to the demand for liquidity confounding the effects of supply. Similar results are obtained for other asset prices, as we later describe. These observations motivate our intraday analysis to identify the causal effects of swap lines which follows.

2.2 Data

We obtain intraday asset price data from FirstRate Data and Refinitiv. In particular, we obtain opening prices, closing prices, and trading volumes by one minute bar for futures contracts and spot exchange rates from FirstRate Data. We obtain opening bids and asks, closing bids and asks, and number of bids and asks for forwards and

[4]Temporary swap lines were with the Reserve Bank of Australia, Banco Central do Brasil, Danmarks NationalBank, Bank of Korea, Banco de Mexico, Norges Bank, Reserve Bank of New Zealand, Monetary Authority of Singapore, and Sveriges Riksbank. Standing facilities are with the Bank of Canada, Bank of England, Bank of Japan, European Central Bank, and Swiss National Bank.

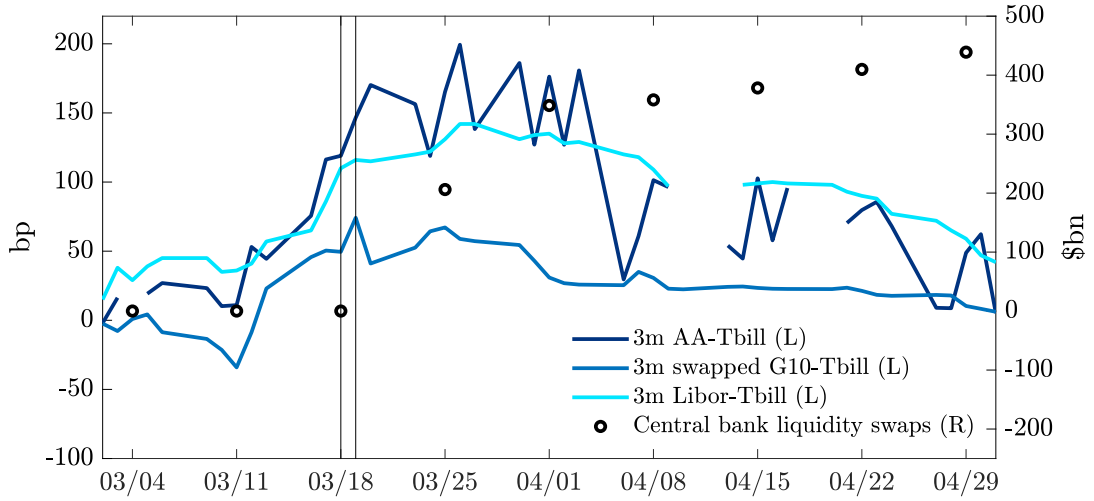


Figure 1: swap line usage and liquidity premia

Notes: vertical lines denote announcement dates. Swap line usage, spread between three-month AA nonfinancial commercial paper and Treasury bills, and spread between three-month Libor and Treasury bills from FRED. Spread between three-month swapped G10 government bonds and Treasury bills from Du et al. (2018a), updated through 2020 and shared with us by Wenxin Du.

OIS rates from Refinitiv. We average the data for bids and asks.

We obtain futures data on interest rates, equities, and bonds. For interest rate futures, we obtain data for Fed funds futures (both the contract settling in the current month and three months ahead), the current three-month Libor future, and Eurodollar futures linked to the three-month Libor rate prevailing in three months, six months, nine months, and 12 months. For equity futures, we obtain data for the e-mini S&P 500, Stoxx 40, FTSE 100, Nikkei 225, and MSCI EM equity index contracts with the nearest settlement, as well as the VIX contract with the nearest settlement. For bond futures, we obtain data for two-, five-, 10-, and 30-year Treasuries, 10-year Gilts, Euro shatz (1.75-2.25 year maturity), Euro bobl (4.5-5.5 year maturity), Euro bund (8.5-10.5 year maturity), and Euro buxl (24.0-35.0 year maturity) contracts with the nearest settlement.

We obtain spot dollar exchange rates, three-month forward dollar exchange rates, and three-month OIS rates for seven G10 currencies: the Australian dollar (AUD), Canadian dollar (CAD), Swiss franc (CHF), Euro (EUR), British pound (GBP), Japanese yen (JPY), and New Zealand dollar (NZD). We also obtain currency futures data for four emerging markets: the Brazilian real (BRL), Mexican peso (MXN), Russian ruble (RUB), and South African rand (ZAR). We finally obtain the three-

month dollar OIS rate.

We focus on futures contracts for interest rates, equities, and bonds because several of the announcements we study occur outside of regular market hours for the underlying assets on the relevant exchanges. Where spot prices for these underlying assets are available (from Refinitiv), we have verified in all cases that the responses of spot prices and the nearest futures prices are very similar. Because trading is more thin around several of the announcements in the 2007-2010 period even using futures prices, we focus on the March 2020 announcements in the main text.

2.3 Methodology

We follow the literature on the high frequency analysis of conventional monetary policy shocks in focusing on asset price responses in a one-hour window around each swap line announcement. In particular, for security i around an announcement at t, let p_{it}^- denote the last closing price 10 minutes prior to the announcement time, but no more than 20 minutes prior to the announcement time.[5] Let p_{it}^+ denote the first opening price 20 minutes after the announcement time, but no more than 40 minutes after the announcement time. We define the response of security i around the announcement (in basis points) as

$$\text{response}_{it} \equiv 10000(\log p_{it}^+ - \log p_{it}^-).$$

For interest rate futures, we multiply this by minus one to report the change in the implied interest rate. For forward premiums, $\log p_{it}$ is the forward premium, and for CIP deviations it is the log dollar OIS rate less synthetic dollar OIS rate. For averages across securities (such as the average exchange rate response), we compute simple averages across the relevant securities.

We build on Krishnamurthy and Vissing-Jorgensen (2011) in assessing the statistical significance of these responses as follows. For concreteness, consider the March 19, 2020 and March 20, 2020 announcements at 9:00 EDT and 10:00 EDT, respectively, studied in the next section. For every hour on every trading day in March 2020

[5] We define the announcement time as the press release time on the Federal Reserve website. We have verified that the first articles referencing these announcements on Factiva occur within a few minutes of the press release time. For instance, the first article referencing the March 19, 2020 press release at 9:00 EDT was published at 9:13 EDT. The first article referencing the March 20, 2020 press release at 10:00 EDT was published at 10:00 EDT.

(denoted t), we follow the above approach in defining the response of each security i around t. For each security i, we run the OLS regression

$$\text{response}_{it} = \alpha_i + \beta_i 1\{\text{announcement at } t\} + \epsilon_{it}.$$

We then report the statistical significance of the estimated coefficient $\hat{\beta}_i$.[6] In other words, we report statistical significance under the null that there is no difference in the response around dollar swap line announcements versus other hours in March 2020. This will be conservative if there were other, non-swap line related announcements during this period which moved asset prices in a similar direction, as seems likely for other conventional and unconventional policies.

2.4 Main results

Tables 1 and 2 report our main results for the March 19, 2020 and March 20, 2020 announcements separately, as well as the cumulative response in the final column. We report the statistical significance as computed above in the last column. Appendix C depicts trading volumes around each announcement. For all securities and announcements emphasized here, there is non-zero trading volume in the minutes before and after each announcement.

The first panel of Table 1 summarizes the response of interest rates from futures contracts. There is neither an economically nor statistically significant response of expected Fed funds rates in the current month or three months ahead,[7] indicating that the expansion of dollar swap lines was not expected to affect the path of policy rates at least in the short term. By contrast, there are economically and statistically significant declines in three-month Libor rates, of $12bp$ cumulatively for the current contract and $5bp$ cumulatively for the 12 month ahead contract, with monotonically declining responses in between. Figure 2 depicts the two hours around each announcement for each contract. The sharp declines in Libor rates around each announcement are evident. While these responses may reflect a decline in counterparty risk among

[6] Note that the sum of the estimated $\hat{\alpha}_i$ and $\hat{\beta}_i$ coefficients equals the average response of security i around the March 19, 2020 and March 20, 2020 announcements.

[7] Following the literature, we multiply the response of the current Fed funds rate by $\frac{T}{T-t-1}$, where T denotes the number of days in the month and t denotes here the day of the announcement. This is because the price of the current contract reflects the Fed funds rate prevailing throughout the month, including the $t-1$ days which have already elapsed by the time of the announcement.

	3/19/20	3/20/20	Sum
Interest rate futures			
Fed funds, current contract	1	-1	1
Fed funds, 3 mo ahead	0	0	0
Libor, 3 mo	-7	-5	-12***
Eurodollar, 3 mo ahead	-7	-4	-11***
Eurodollar, 6 mo ahead	-6	-3	-9***
Eurodollar, 9 mo ahead	-4	-3	-7***
Eurodollar, 12 mo ahead	-3	-2	-5**
Spot exchange rates			
AUD	-82	-35	-117***
CAD	-65	-19	-84***
CHF	-28	-31	-59***
EUR	-30	-40	-70***
GBP	-6	-81	-87***
JPY	7	-4	3
NZD	-73	-21	-94***
Average	-40	-33	-72***

Table 1: high frequency responses (1/2)

Notes: responses are defined as the log open price of the first one-minute bar with positive trading volume beginning 20 minutes after the press release time, less the log close price of the last one-minute bar with positive trading volume ending 10 minutes before the press release time, multiplied by 10000 (thus reported in *bp*). Interest rate responses multiplied by minus one, so these correspond to responses of yields. Response is missing (denoted .) if there is no trading volume in 10-20 minutes prior to the press release time or 20-40 minutes after the press release time. ***, **, and * denote statistical significance of cumulative responses at 10%, 5%, and 1% levels, respectively.

	3/19/20	3/20/20	Sum
Forward premiums			
AUD, 3 mo	0	3	4
CAD, 3 mo	-0	8	7***
CHF, 3 mo	5	28	34***
EUR, 3 mo	6	43	49***
GBP, 3 mo	-2	19	17***
JPY, 3 mo	-2	40	38***
NZD, 3 mo	-1	0	-1
Average, 3 mo	1	20	21***
Equity index futures			
S&P 500	40	112	151
Euro Stoxx 50	30	102	132
FTSE 100	-6	-24	-30
Nikkei 225	97	108	205*
VIX	-33	-382	-415***
Bond futures			
Treasury, 10 yr	23	-9	13
Treasury, 30 yr	49	-30	20

Table 2: high frequency responses (2/2)

Notes: responses are defined as the log open price of the first one-minute bar with positive trading volume beginning 20 minutes after the press release time, less the log close price of the last one-minute bar with positive trading volume ending 10 minutes before the press release time, multiplied by 10000 (thus reported in *bp*). Response is missing (denoted .) if there is no trading volume in 10-20 minutes prior to the press release time or 20-40 minutes after the press release time. ***, **, and * denote statistical significance of cumulative responses at 10%, 5%, and 1% levels, respectively.

financial institutions since Libor is an unsecured rate, our preferred interpretation is that this reflects a decline in the liquidity premium, given the daily comovement between the three-month Libor/Treasury bill spread and other measures of liquidity premia from Figure 1 over this period. Appendix B reports these same series over the longer 1997-2020 period, and their comovement remains evident.

The second panel of Table 1 summarizes the response of spot exchange rates. Throughout the paper, we write all exchange rates as foreign currency per dollar. As is evident, the dollar depreciates by an economically and statistically significant amount versus all currencies except the Japanese yen. Taking the simple average across these seven currencies, we conclude that the dollar depreciates by $72bp$ cumulatively. Figure 3 depicts these responses. As is evident, the dollar depreciation is sharp around (or a few minutes slightly before) the announcement in most cases. Appendix C demonstrates that similar results are obtained for the four emerging market currencies in our data, though trading volume is more thin than for the G10 currencies. The dollar depreciates by $117bp$ cumulatively against these currencies, also statistically significant at conventional levels.

The first panel of Table 2 summarizes the response of three-month forward premiums, defined as the log forward rate less log spot rate, annualized. The forward premiums rise by an economically and statistically significant amount for all currencies except the Australian dollar and New Zealand dollar, driven in particular by the March 20 announcement of an increased frequency of standing swap line operations. On average, the forward premium rises by $21bp$ across both announcements. Figure 4 depicts these responses, which are again sharp around the announcement in most cases. Appendix C reports the responses of three-month CIP deviations using OIS rates, defined as the dollar OIS rate less the foreign OIS rate plus the forward premium. For the four currencies with sufficiently frequent intraday quotes for OIS rates to obtain estimates, the response of the three-month CIP deviation is very close to the response of the forward premium, as the response of the OIS rate differential is small. We conclude that our estimated $21bp$ rise in the average forward premium across all seven currencies corresponds to a roughly $21bp$ compression in the average CIP deviation across these currencies, recalling that it was negative to begin with.

The second panel of Table 2 summarizes the response of equities. The S&P 500 rises by a cumulative $151bp$ across these announcements. Two of the three foreign stock markets also rise in their local currencies, but all of them would rise in dollars

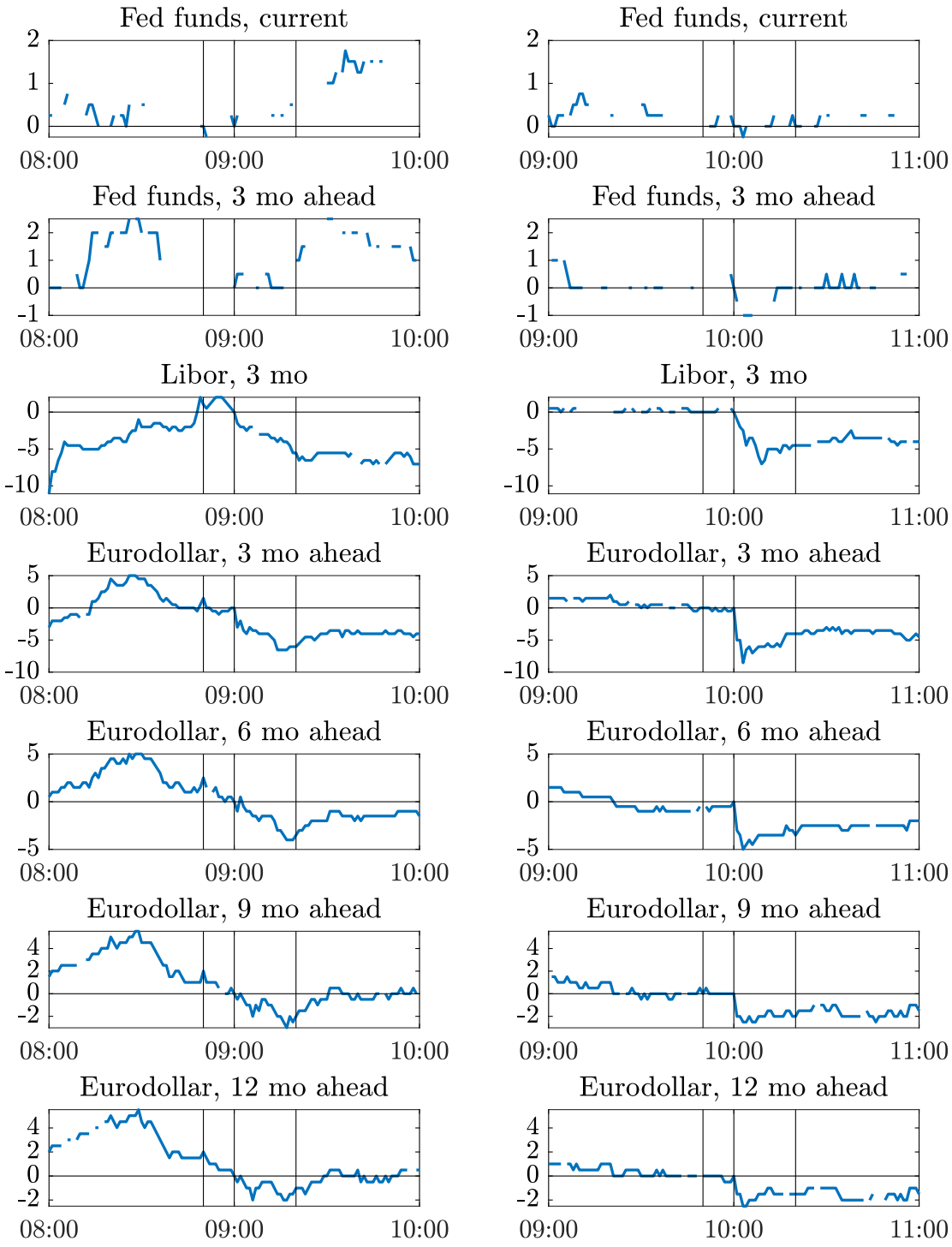


Figure 2: interest rate futures on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict −1 times log open price by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

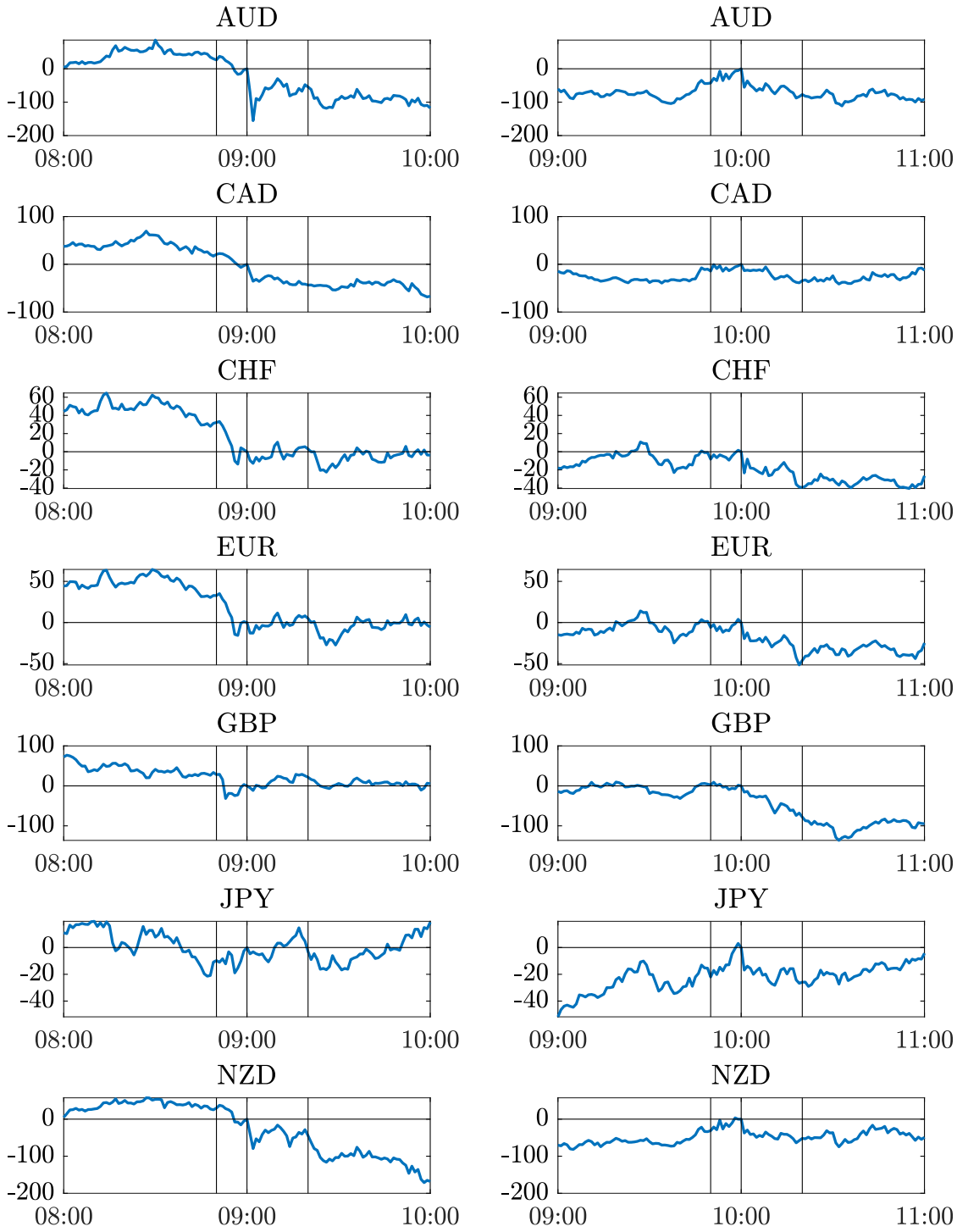


Figure 3: spot exchange rates on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict log open price (foreign per dollar) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

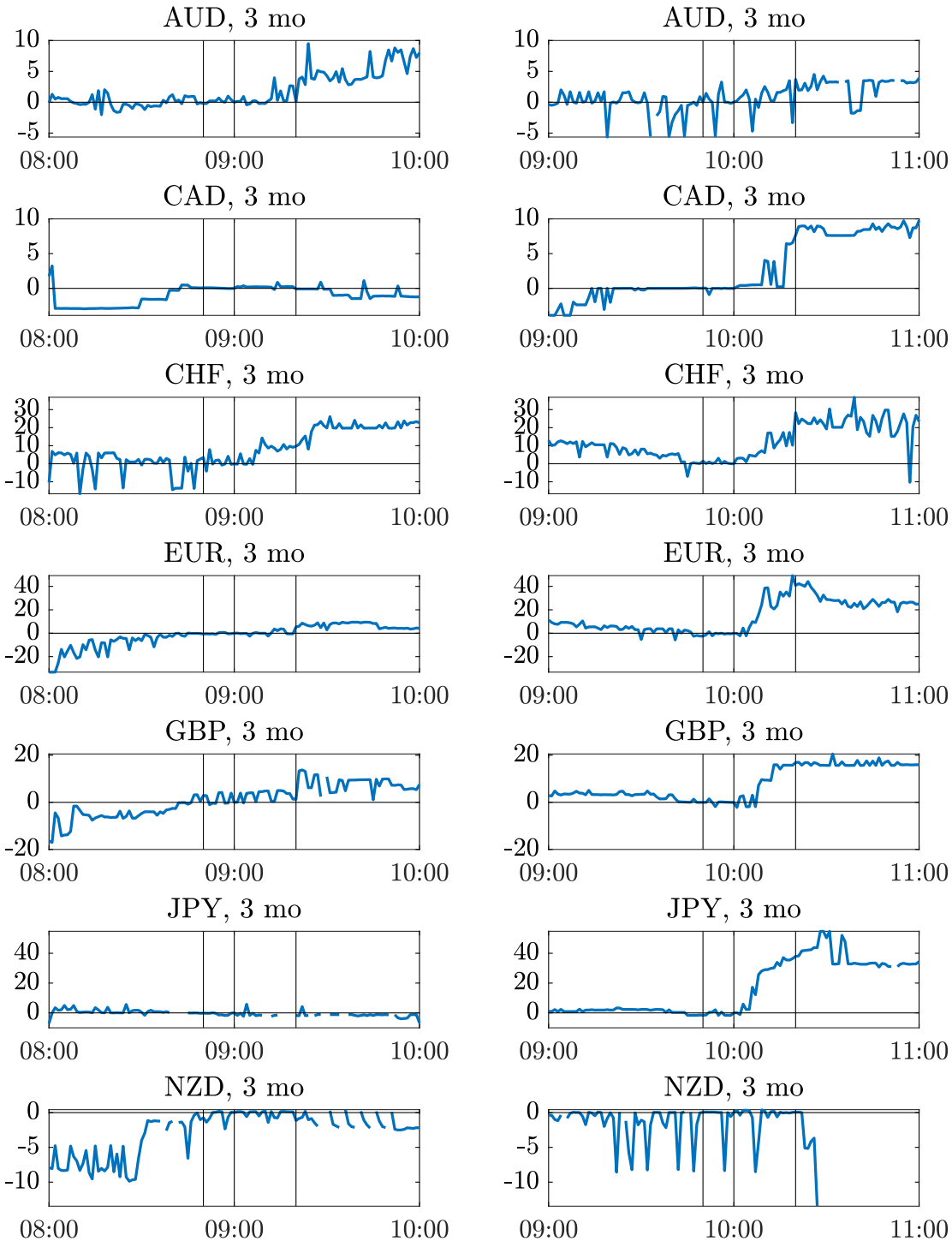


Figure 4: forward premiums on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict forward premium at open by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

given the dollar depreciation discussed above. The VIX falls by an economically and statistically significant 415*bp* cumulatively. While the (local currency) stock market responses are otherwise insignificantly or marginally different from zero, Figure 5 demonstrates clear, sharp rises in the markets around the March 20, 2020 announcement in particular. Appendix C demonstrates similar results for the MSCI EM Equity Index. Overall, we view this as reasonably compelling evidence that equity markets rise and the VIX falls around news of expanded dollar swap lines.

Lastly, the third panel of Table 2 and the bottom two rows of Figure 5 summarize the response of long-term Treasury bonds from futures contracts. These responses are more mixed, with fairly sharp rises on the first announcement, but declines on the second. The cumulative effect is a mild increase in long-term Treasury bond prices, notably smaller than most of the equity market responses, and in no case statistically different from zero. Appendix C demonstrates similar results for Treasury bonds of other maturities as well as Gilts and Euro bonds. We conclude that the response of government bond prices is more muted than for the other securities we study.

2.5 Discussion and additional results

We finally discuss several additional results and place our estimates in context.

One-day changes Appendix C presents the one-day changes in each security price, rather than the high frequency response. Using the cumulative two-day change in these asset prices, the dollar appreciated by 66*bp*, the S&P 500 futures price fell by 486*bp*, and 30-year Treasury bond futures price rose by 488*bp*, consistent with the flight to safety during this period. The interest rate responses are now inconsistent across announcements, some foreign currencies appreciate versus the dollar while others depreciate, and the CIP deviations widen on average on March 19. Overall, this underscores the importance of focusing on intraday windows to identify the effects of swap lines on our asset prices of interest.

2007-2010 announcements Appendix D also reports the high frequency response of asset prices around the six announcements during the 2007-2010 period. In many cases we do not observe responses within our windows, in part because several of these announcements occurred in the very early morning. However, where we have available data, we broadly find that our conclusions from the March 2020 announcements are

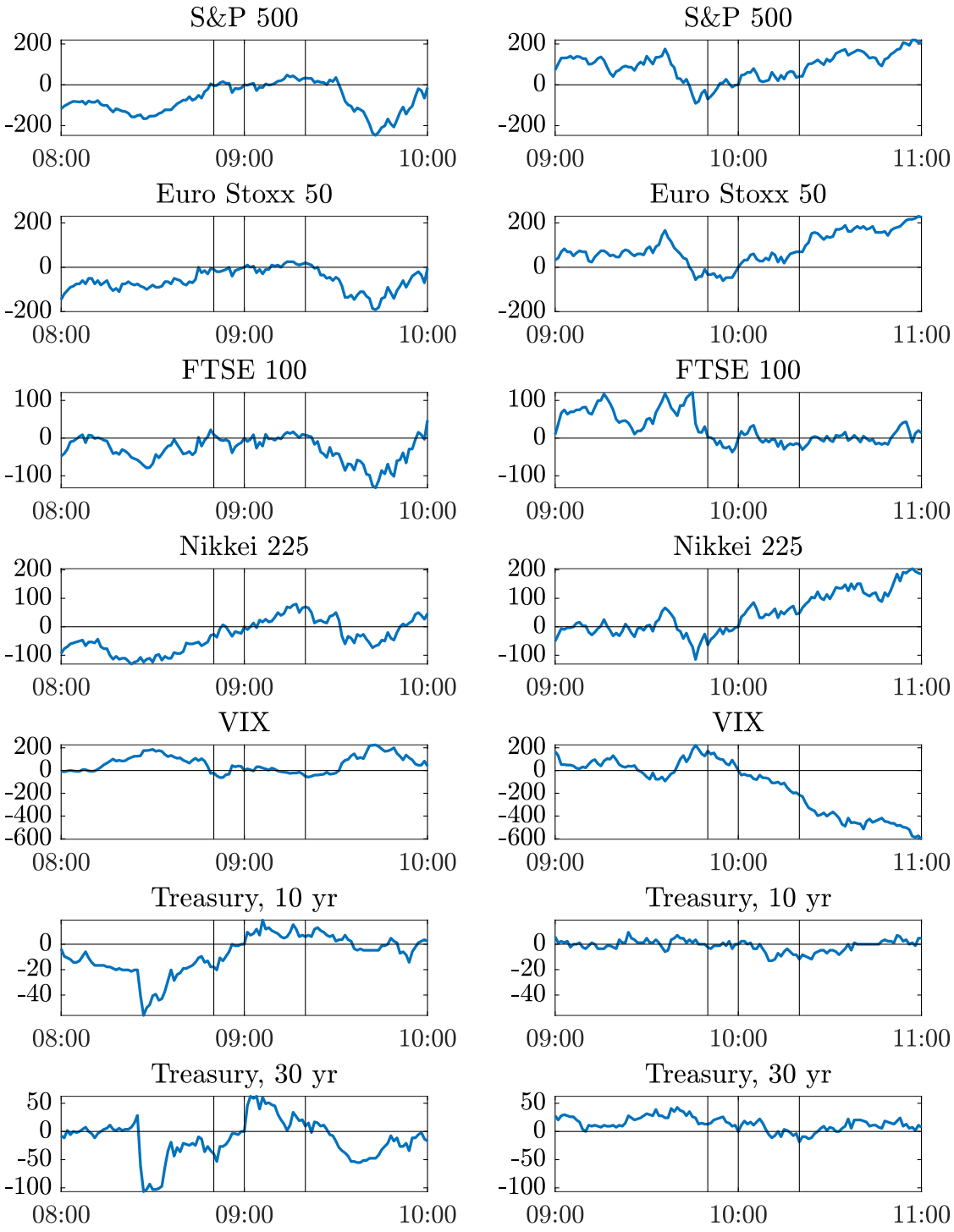


Figure 5: equity and bond futures on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict log open price by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

robust: these announcements caused a reduction in Eurodollar rates, a depreciation of the dollar (except against the yen), a rise in forward premiums, an increase in the S&P 500, and a mixed and muted response of Treasury bond prices.

Relationship to other estimates The responses of CIP deviations we estimate are comparable to estimates using other methodologies. In particular, Bahaj and Reis (2022) estimate that the November 30, 2011 reduction in the cost of accessing swap lines by $50bp$ lowered the average CIP deviation price quote by $28bp$ relative to currencies not covered by these swap lines (their Table 1). Our intraday estimates uncover aggregate responses of CIP deviations to swap line announcements of similar magnitude, and also suggest that the cross-sectional identification of CIP deviations in Bahaj and Reis (2022) is not "missing" a large intercept: the forward premium responses of the Australian and New Zealand dollars in Table 2 are indeed the smallest of the seven currencies we estimate, and these are the two G10 currencies in our sample without standing facilities affected by the March 20 announcement.[8]

Our findings are also consistent with the literature estimating the relationship between liquidity premia and exchange rates. In particular, Jiang et al. (2021) estimate that a fall in the annualized Treasury basis by $1pp$ results in a $10pp$ depreciation in the dollar (their Table III). Engel and Wu (2022) estimate with a slightly different specification and sample period that a fall in the annualized Treasury basis by $1pp$ results in a $6pp$ depreciation of the dollar (their Table 1 or 2). We estimate a $12bp$ decline in the annualized three-month Libor rate and $72bp$ depreciation of the dollar (our Table 1). Linearly extrapolating, it follows that a $1pp$ decline in the annualized three-month Libor rate is associated with a $0.72 \times (1/0.12) = 6pp$ depreciation, comparable to these papers.[9] In other words, the relationship between liquidity premia and exchange rates conditional on our swap line announcements is consistent with the unconditional relationship between these variables uncovered in the prior literature.

[8]This is, however, not true for all asset prices we study — for instance, we find a sharp appreciation of the Australian and New Zealand dollars on March 20, and an appreciation of emerging market currencies to both announcements even though they did not have access to swap lines.

[9]Since we estimate a very small response of Fed funds and OIS rates, a reasonable assumption is that intraday Treasury bill rates also are unaffected. Our estimates are thus comparable to Jiang et al. (2021) and Engel and Wu (2022) because the unconditional volatility of the three-month Libor/Treasury bill basis is of the same order of magnitude as the Treasury bases they study.

3 Understanding these effects

We now demonstrate that the observed responses to swap line announcements are qualitatively consistent with a general equilibrium model in which dollar swap lines increase the supply of safe dollar liquidity, and in which liquidity premia, CIP deviations, exchange rates, and other asset prices are jointly determined.

3.1 Environment

Consider a two-country global economy comprised of the U.S. (Home) and Foreign. The representative agents in each country receive endowments y and y^*, respectively. Their lifetime utilities are

$$\sum_{t=0}^{\infty} \mathbb{E}_t \beta^t \left[\log c_t + \log \Omega_t(b^s_{Ht})\right],$$
$$\sum_{t=0}^{\infty} \mathbb{E}_t \beta^t \left[\log c^*_t + \log \Omega^*_t(b^{s*}_{Ht})\right],$$

respectively, where c_t and c^*_t are consumption aggregators and $\Omega_t(\cdot)$ and $\Omega^*_t(\cdot)$ denote non-pecuniary value from certain dollar-denominated assets described below. U.S. consumption is an aggregate of consumption of the domestic good c_{Ht} and of the imported good c_{Ft} with home bias indexed by ς and elasticity of substitution σ:

$$c_t = \left(\left(\frac{1}{2} + \varsigma\right) c_{Ht}^{\frac{\sigma-1}{\sigma}} + \left(\frac{1}{2} - \varsigma\right) c_{Ft}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}.$$

The consumption of the Foreign agent c^*_t is symmetrically defined over c^*_{Ht} and c^*_{Ft}. Trade in goods is frictionless, so the law of one price holds for the U.S. endowment and the Foreign endowment. Without loss of generality, we let the price of the U.S. consumption bundle be the numeraire. We denote q_t the real exchange rate, the price of the Home consumption bundle relative to the Foreign bundle.

Before introducing swap lines, there are four assets traded internationally. We refer to assets paying in units of the U.S. (Foreign) consumption bundle as dollar-denominated (Foreign-denominated). First, $\{b^s_{Ht}, b^{s*}_{Ht}\}$ denote the positions of agents in a "safe dollar bond" which pays r^s_t and provides non-pecuniary value in each country, such as reserves or Treasury bills. We assume a particularly convenient

functional form

$$\Omega_t(b^s_{Ht}) \equiv \exp\left(\lambda\omega\left(b^s_{Ht}/\bar{c}_t\right) - \left(1/\epsilon^d\right)\left(b^s_{Ht}\right)^2/\bar{c}_t\right),$$
$$\Omega^*_t(b^{s*}_{Ht}) \equiv \exp\left(\omega\left(q_t b^{s*}_{Ht}/\bar{c}^*_t\right) - \left(1/\epsilon^d\right)q_t\left(b^{s*}_{Ht}\right)^2/\bar{c}^*_t\right),$$

where $\bar{c}_t = c_t$ and $\bar{c}^*_t = c^*_t$ are taken as given in each agent's optimization for simplicity. Here the parameters ω, λ, and ϵ^d control the level of the global demand for these assets, the relative demand in the U.S. versus Foreign, and the elasticity of demand with respect to the price of the asset, respectively. Second, $\{b_{Ht}, b^*_{Ht}\}$ denote the positions of agents in an "other dollar bond" which pays r_t and does not provide non-pecuniary value, such as dollar Libor deposits. Third, $\{b_{Ft}, b^*_{Ft}\}$ denote the positions of agents in a Foreign-denominated asset which pays r^*_t and also does not provide non-pecuniary value, such as Foreign-denominated interbank loans or government bonds. Fourth, $\{\eta_t, \eta^*_t\}$ denote the positions of agents in a forward contract to sell one unit of the U.S. consumption good for f_t units of the Foreign consumption good at $t+1$.

There are three frictions in asset market trade. First, Foreign pays a quadratic cost in its net position in dollar-denominated assets

$$\frac{1}{2}\kappa_{fx} q_t \left[b^{s*}_{Ht} + b^*_{Ht} - \eta^*_t\right]^2,$$

capturing the costs of having unhedged exchange rate exposure. Second, Foreign faces a borrowing constraint in dollar Libor

$$b^*_{Ht} \geq \underline{b}^*_H,$$

which, if binding, means that Foreign is not marginal in this market. Third, the U.S. pays quadratic costs in its position in each asset

$$\frac{1}{2}\kappa_{bs}\left[\left(b^s_{Ht}\right)^2 + \left(b_{Ht}\right)^2 + \left(q_t^{-1}b_{Ft}\right)^2 + \left(\eta_t\right)^2\right],$$

capturing the balance sheet costs arising from regulatory requirements. $\kappa_{fx} > 0$, $\underline{b}^*_H \leq 0$, and $\kappa_{bs} > 0$ are parameters capturing the magnitude of these costs and tightness of the Foreign borrowing constraint.

The U.S. government inelastically issues $\bar{b}^s_H > 0$ units of the safe dollar asset, paying the interest via lump-sum taxes on the U.S. agent. Market clearing thus

requires

$$b^s_{Ht} + b^{s*}_{Ht} = \bar{b}^s_H, \tag{1}$$

$$b_{Ht} + b^*_{Ht} = 0, \tag{2}$$

$$b_{Ft} + b^*_{Ft} = 0, \tag{3}$$

$$\eta_t + \eta^*_t = 0, \tag{4}$$

$$c_{Ht} + c^*_{Ht} = y_t. \tag{5}$$

By Walras' Law, the Foreign goods market clears as well.

3.2 Key equilibrium conditions

We now outline the intertemporal optimality conditions for safe dollar bonds, other dollar bonds, and forwards which are central to understanding the mechanics of the model. All other equilibrium conditions are provided in appendix E.

First, the optimality conditions for the safe dollar bonds $\{b^s_{Ht}, b^{s*}_{Ht}\}$ are

$$1 + \kappa_{bs} b^s_{Ht} = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}}(1 + r^s_t) + \lambda \omega_t - \frac{1}{\epsilon^d} b^s_{Ht}, \tag{6}$$

$$1 + \kappa_{fx} u h^*_t = \mathbb{E}_t \beta \frac{c^*_t}{c^*_{t+1}} \frac{q_{t+1}}{q_t}(1 + r^s_t) + \omega_t - \frac{1}{\epsilon^d} b^{s*}_{Ht}, \tag{7}$$

where

$$u h^*_t \equiv b^{s*}_{Ht} + b^*_{Ht} - \eta^*_t$$

denotes the unhedged dollar exposure of Foreign. The marginal cost of purchasing an additional safe dollar bond includes the balance sheet cost at Home and cost of increasing Foreign's unhedged dollar exposure. The marginal benefit includes the non-pecuniary value provided by these bonds.

Second, the optimality conditions for the other dollar bonds $\{b_{Ht}, b^*_{Ht}\}$ are

$$1 + \kappa_{bs} b_{Ht} = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}}(1 + r_t), \tag{8}$$

$$1 + \kappa_{fx} u h^*_t \geq \mathbb{E}_t \beta \frac{c^*_t}{c^*_{t+1}} \frac{q_{t+1}}{q_t}(1 + r_t), \tag{9}$$

where the second condition holds with equality if the Foreign borrowing constraint in

this asset is slack.

Third, the optimality conditions for the forward contracts $\{\eta_t, \eta_t^*\}$ are

$$\kappa_{bs}\eta_t = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}} \left[q_{t+1}^{-1} f_t - 1\right], \tag{10}$$

$$-\kappa_{fx} u h_t^* = \mathbb{E}_t \beta \frac{c_t^*}{c_{t+1}^*} \frac{q_{t+1}}{q_t} \left[q_{t+1}^{-1} f_t - 1\right]. \tag{11}$$

The right-hand sides reflect the risk-neutral return to the U.S. and Foreign agents, respectively, of buying one unit of the U.S. consumption bundle at $t+1$ and selling it at the forward price f_t contracted in the prior period. The left-hand sides reflect the effect on Home's balance sheet costs and Foreign's unhedged dollar exposure, respectively, of entering into such a contract.

We now present our first main result, a characterization of the portfolios and spreads in this economy at the deterministic steady-state:[10]

Proposition 1. *Assume that λ is sufficiently close to one, $\underline{b}_H^*$ is sufficiently close to zero, and ω is sufficiently large. Then in the deterministic steady-state:*

- *the U.S. and Foreign own safe dollar bonds ($b_{H,s}^* \in (0, \bar{b}_{H,s}^*)$);*
- *Foreign borrows in other dollar bonds from the U.S. until the constraint ($b_H^{s*} = \underline{b}_H^{s*}$);*
- *Foreign sells dollars forward to the U.S. ($\eta^* > 0$) but maintains unhedged dollar exposure ($uh^* > 0$);*
- *the return on other dollar bonds are below synthetic dollar bonds ($1 + r < \frac{q}{f}(1 + r^*)$);*
- *the return on safe dollar bonds is below other dollar bonds ($r^s < r$).*

When λ is sufficiently close to one, the non-pecuniary value from safe dollar bonds is sufficiently similar in both countries that, from (6)-(7), both own positive amounts of the outstanding supply of safe dollar bonds. Given a sufficiently tight borrowing constraint in other dollar bonds $\underline{b}_H^*$, (8)-(9) then imply that the constraint will bind around the steady-state of interest. Intuitively, Foreign's long position in safe dollar bonds will motivate it to borrow in other dollar bonds to reduce its unhedged dollar

[10]The proofs of this proposition and the next one are provided in appendix F.

exposure. (10)-(11) imply that Foreign will also sell dollars forward to reduce its dollar exposure but, given the balance sheet costs incurred in the U.S. from taking the other side, Foreign will retain some unhedged exposure in steady-state and there will be a deviation from CIP whereby the return on synthetic dollar bonds exceeds other dollar bonds. Finally, provided the value of liquidity ω is sufficiently high, there will be a liquidity premium whereby the return on safe dollar bonds is below other dollar bonds.

3.3 Effects of dollar swap lines

We now introduce dollar swap lines in the model.

We model the swap lines as a commitment by the U.S. agent to lend an unlimited amount of dollars to the Foreign agent against Foreign-denominated collateral at a dollar-denominated interest rate r_t^{sw}.[11] We generalize Foreign's non-pecuniary value of dollar liquidity to be

$$\Omega_t^*(b_{Ht}^{s*} + \nu_t^{sw} sw_t^*),$$

where ν_t^{sw} is the relative liquidity of dollars obtained via swap lines versus the safe dollar bond (perhaps equal to one). The Foreign agent can receive dollars via the swap lines but cannot lend them, so it faces the constraint

$$sw_t^* \geq 0.$$

Crucially, dollar swap lines provide liquidity in Foreign without exacerbating the costs of having unhedged exchange rate exposure. This is because swap lines simultaneously provide a dollar asset to Foreign agents but also create a dollar liability, the obligation to return those dollars at the end of the period.

The optimality condition with respect to Foreign bonds swapped into dollars in this way implies

$$\nu_t^{sw}\left(\omega_t - \frac{1}{\epsilon^d}\left(b_{Ht}^{s*} + \nu_t^{sw} sw_t^*\right)\right) \leq \mathbb{E}_t \beta \frac{c_t^*}{c_{t+1}^*} \frac{q_{t+1}}{q_t} r_t^{sw}, \tag{12}$$

[11] This captures the standing swap line facilities between the Federal Reserve and five central banks described in footnote 4, for which there has been no cap on dollars drawn since October 2008. By contrast, the temporary facilities are capped and hence the price of the swap line adjusts to clear the market given fixed supply. The vast majority of swap line usage has been via the five standing facilities, so we model these here. Nonetheless, the effects of increasing the supply of dollar swaps, letting the price clear the market, is similar to the effects of lowering the price as studied here.

with equality if there is positive take-up $sw_t^* > 0$. The right-hand side is the risk neutral cost of the swap line for the Foreign agent. The left-hand side is the marginal value of liquidity it provides.

We now characterize the marginal effects of a reduction in the cost of accessing swap lines r_t^{sw} or an increase in the liquidity value they provide ν_t^{sw}. The former captures events such as the March 19, 2020 announcement that new swap lines would become available for some central banks, as the cost of accessing them effectively fell from being infinite. The latter captures events such as the March 20, 2020 announcement that the frequency of standing swap line operations would increase from weekly to daily, as this presumably increased their liquidity value.

Analytical results in steady-state We first analytically characterize the effects of permanent changes to r^{sw} and ν^{sw} on steady-state, assuming initial values with positive take-up of swap lines in the deterministic steady-state. The following proposition characterizes the effect on the steady-state portfolios and spreads described in Proposition 1, as well as the effect on the dollar exchange rate:

Proposition 2. *Assume the parametric conditions of Proposition 1 and positive take-up of swap lines in the deterministic steady-state. Then given a reduction in r^{sw} or increase in ν^{sw}:*

- *Foreign ownership of safe dollar bonds falls ($db_H^{s*} < 0$);*
- *the Foreign unhedged dollar exposure falls ($duh^* < 0$) and its sales of dollars forward falls ($d\eta^* < 0$);*
- *the CIP deviation compresses ($d\left[1 + r - \frac{q}{f}(1 + r^*)\right] > 0$) because the forward premium rises ($d\left[\log f - \log q\right] > 0$);*
- *the liquidity premium compresses ($d\left[r - r^s\right] < 0$);*
- *the dollar depreciates ($dq < 0$), provided the initial return on safe dollar bonds r^s and cost of swap lines r^{sw} are sufficiently small.*

When swap lines are cheaper or more useful in providing liquidity, Foreign substitutes away from safe dollar bonds and towards swap lines. This reduces its unhedged dollar exposure and thus its need for hedging, in turn compressing the deviation from

CIP. Since Home must be induced to absorb the greater residual supply of safe dollar bonds, the return on these bonds must rise and thus the liquidity premium also falls.

The effect of swap lines on the dollar exchange rate reflects their effect on relative wealth and thus relative demand for goods. The effect on relative wealth is summarized by the effect on

$$r^s b_H^{s*} + \left(q^{-1} f - 1\right) \eta^* - r^{sw} sw^*,$$

which is Foreign's steady-state interest income earned on safe dollar bonds, earned on forward contracts, and paid on swap lines, respectively. The rise in the return on safe dollar bonds r^s and the forward premium $\log f - \log q$, the fall in the Foreign demand for hedging η^*, and a fall in the cost of swap lines r^{sw} all redistribute wealth to Foreign and thus depreciate the dollar, given home bias.[12] However, the fall in Foreign saving in safe dollar bonds b_H^{s*} and higher take-up of swap lines sw^* redistribute wealth to Home. When the initial return on safe dollar bonds r^s and cost of swap lines r^{sw} are sufficiently small, these latter effects are small and the dollar indeed depreciates.

Numerical illustration of transitory shocks We now characterize the effects of transitory shocks to r_t^{sw} and ν_t. We depict these in the case of an illustrative parameterization summarized in Table 3, solved using a first-order approximation around the deterministic steady-state. We normalize $y = 1$ and assume $y^* = 1$ for symmetry. We set $\varsigma = 0.3$ so that the expenditure share on domestic goods is 80%, following the evidence for the U.S. in Eaton, Kortum, and Neiman (2016). We set $\sigma = 1.5$ following Backus, Kehoe, and Kydland (1994). We set $\underline{b}_H^* = 0$ for simplicity; it follows then that $r = r^*$ in steady-state. Solving the model at a quarterly frequency, we set β to target annualized real interest rates in each country of 0.75%. We set $\bar{b}_H^s = 1$ so that the outstanding supply of safe dollar bonds is 25% of annual output. This is roughly double the outstanding supply of Treasury bills at the end of 2019, capturing that these safe dollar bonds are also meant to encompass reserves and other money-like assets. We set κ_{fx}, κ_{bs}, λ, and ω to jointly target a real exchange rate of one, an annualized CIP deviation of -0.5%, an annualized liquidity premium of 0.5%, and Foreign ownership of safe dollar bonds equal to 60% of the outstanding supply. The latter is consistent with foreigners owning a greater share of Treasuries

[12]Note that the decline in η^* redistributes to Foreign because the steady-state forward premium $\log f - \log q$ is negative, reflecting the CIP deviation in Proposition 1.

	Value	Rationale
y	1	Normalization
y^*	1	$y^* = y$
ς	0.3	Eaton et al. (2016)
σ	1.5	Backus et al. (1994)
$\underline{b}^*_H$	0	$r = r^*$
β	$(1 + 0.0075/4)^{-1}$	$r^* = 0.75\%/4$
$\bar{b}_{H,s}$	1	25% of annual U.S. output
κ_{fx}	0.004, 0.004	$\begin{cases} q = 1, \\ 1 + r - \frac{q}{f}(1 + r^*) = -0.5\%/4, \\ b^{s*}_H / \bar{b}^s_H = 60\%, \\ r - r^s = 0.5\%/4 \end{cases}$
κ_{bs}	0.004	
ω	0.12, 0.03	
λ	0.67, 0.71	
r^{sw}	$0.0075/4$	$r^{sw} = r^*$
ν^{sw}	0.75	$sw^* = 0$

Table 3: illustrative calibration

Notes: in cases where two parameter values are given, these correspond to values given $\epsilon^d = 5$ and $\epsilon^d = 25$, respectively.

than (non-Federal Reserve) domestic residents in recent years, as reported by Tabova and Warnock (2023). Finally, we study transitory shocks around a steady-state in which $r^{sw} = r^*$ and ν^{sw} is calibrated so that $sw^* = 0$.

Figure 6 depicts the impulse responses to a -0.5% annualized innovation to r^{sw}_t, assuming the latter follows an AR(1) with persistence 0.3. The latter implies that the induced swap line usage is essentially eliminated after one year, consistent with the pattern of swap line usage after March 2020. We simulate two cases, one with $\epsilon^d = 5$ and another with $\epsilon^d = 25$. In both cases, the more generous pricing of swap lines induces an increase in swap line usage (top middle panel); a substitution away from safe dollar bonds by Foreign (top right panel); an associated compression of the CIP deviation (bottom left panel); compression in the liquidity premium (bottom middle panel); and depreciation of the dollar (bottom right panel). All of these are consistent with the steady-state comparative statics from Proposition 2. A higher value of ϵ^d raises the elasticity of swap line usage to a change in its pricing, and the associated substitution away from safe dollar bonds, decline in hedging demand, and thus compression of the CIP deviation.[13] The other asset price responses are not

[13]We note that the nearly $400bn in swap line usage in the two weeks following the March 2020 announcements corresponds to roughly 2% of 2019 U.S. GDP, within the range of the simulated responses here.

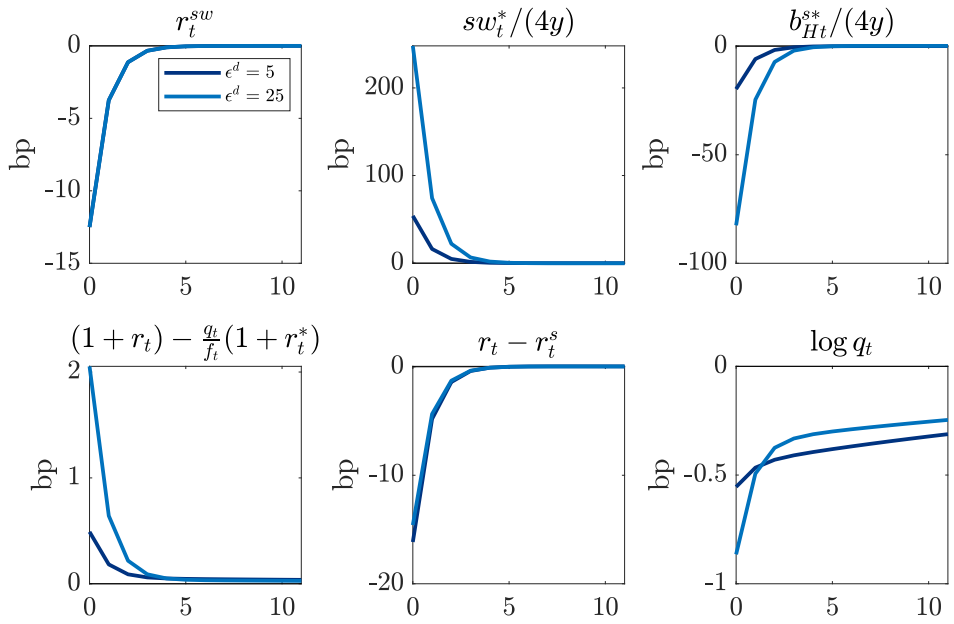


Figure 6: effects of shock to r_t^{sw}

Notes: r_t^{sw} assumed to follow AR(1) process with persistence 0.3.

much affected. Appendix G provides the impulse responses to a positive innovation to ν_t^{sw} which generates the same patterns.

3.4 Discussion and additional results

We now place our theoretical results in context, and we discuss several additional model implications.

Relationship to literature Bahaj and Reis (2022) prove under a minimal set of conditions that swap lines put a ceiling on CIP deviations. We make more assumptions on the economic environment, with CIP deviations arising as a symptom of the demand for safe dollar assets and need to hedge the associated dollar exposure abroad, following Jiang et al. (2021). In this environment, we show that swap lines put a ceiling on the *liquidity premium* in (12), with implications for CIP deviations but also other asset prices, including the dollar exchange rate.

The effect of swap lines on the dollar exchange rate echoes the mechanism linking liquidity premia and exchange rates in Jiang et al. (2022). These authors study a

general equilibrium environment in which the decline in the Foreign demand for safe dollar assets lowers the seignorage revenues earned by the U.S. and hence depreciates the dollar. This force is at work in our model, and is accompanied by a decline in intermediation profits earned by the U.S. in providing hedging services to Foreign. We note, however, that the magnitude of the dollar depreciation in Figure 6 is two orders of magnitude smaller than the effects of swap line announcements we estimate in the data. One reason for this is that the U.S. real interest rate r rises relative to the Foreign real interest rate r^*, dampening the dollar depreciation on impact. Enriching the model with nominal rigidities and monetary policy in each country which does not perfectly track this behavior of natural rates, we expect that the dollar depreciation on impact of swap lines would be amplified, following Kekre and Lenel (2023). As the latter paper shows, the amplified dollar depreciation in this case reflects a disproportionate increase in U.S. output.

The response of the CIP deviation in Figure 6 is also an order of magnitude smaller than the response to swap line announcements we estimate in the data. One reason for this is that the degree of market segmentation may rise during times of market stress, which is not well captured by the present model (and especially the first-order solution method). A state-dependent degree of market segmentation would be naturally captured by segmentation *within* each country, as via a distinction between households and arbitrageurs, and by a link between the intermediation capacity of arbitrageurs and their level of wealth, as in Kekre and Lenel (2022).

Effects on equities and government bonds Consider an extension of the model to speak to the effects of swap lines on equities and long-term government bonds. Suppose Foreign trades a dollar-denominated consol at price p_t^x which pays x units of the U.S. consumption bundle at all dates. Home inelastically issues one unit of this asset to Foreign, which enters into Foreign's unhedged dollar exposure. Suppose further the asset provides non-pecuniary value which is substitutable with safe dollar bonds but only ν^x times as much as safe dollar bonds. Then Foreign's optimality condition for this asset, using that Foreign owns one unit by market clearing, yields

$$1 + \kappa_{fx} u h_t^* = \mathbb{E}_t \beta \frac{c_t^*}{c_{t+1}^*} \frac{q_{t+1}}{q_t} \frac{x + p_{t+1}^x}{p_t^x} + \nu^x \left(\omega_t - \frac{1}{\epsilon^d} \left(b_{Ht}^{s*} + \nu_t^{sw} s w_t^* + \nu_t^x p_t^x \right) \right).$$

This equation implicitly (and recursively) defines the asset price p_t^x. The left-hand side reflects that this asset exacerbates Foreign's unhedged dollar exposure. The right-hand side reflects that this asset may also provide non-pecuniary liquidity value.

When $\nu^x = 0$, as in the case of equities which do not provide safety/liquidity services, the asset price rises when swap lines are made more generous (that is, r^{sw} falls or ν^{sw} rises). Intuitively, the swap lines lower Foreign's dollar hedging costs on the margin, increasing Foreign demand for the asset and lowering its required return. We interpret this as consistent with the rise in the S&P 500 upon swap line announcements we estimate in the data.[14] Moving beyond a zero/first-order approximation of the model, we expect that the same mechanism can account for the fall in the VIX we estimate upon swap line announcements. News about more generous swap lines would support the price of dollar equities in bad states, reducing downside risk and thus the VIX on impact. Finally, when $\nu^x > 0$, as in the case of long-term Treasury bonds which do provide some liquidity services, there is also a countervailing downward pressure on the asset price because swap lines lower the marginal value of liquidity. This can rationalize the more muted increase in long-term Treasury bond prices upon swap line announcements we estimate in the data.

Other shocks Our model can finally be used to study the effects of a variety of other shocks beyond swap lines. Appendix G characterizes the effects of an increase in the supply of safe dollar bonds $\bar{b}_H^s$, global demand for safe dollar assets ω, Foreign cost of unhedged dollar exposure κ_{fx}, and U.S. balance sheet costs κ_{bs}. We view the first two as particularly interesting.

The response to an increase in $\bar{b}_H^s$ clarifies what makes swap lines distinct from the provision of other forms of dollar liquidity. As with swap lines, the increase in $\bar{b}_H^s$ compresses the liquidity premium and depreciates the dollar. However, it has contrasting effects on Foreign hedging costs and thus the deviation from CIP. This is because both Foreign and the U.S. absorb some of the marginal safe dollar bond supply. The increased Foreign position raises its dollar hedging costs on the margin, increasing its demand to sell dollars forward and widening the CIP deviation.[15] This clarifies that the unique feature of swap lines is that they provide dollar liquidity to foreigners without exacerbating their unhedged dollar exposure.

[14] It is further consistent with the rise in dollar corporate bond prices found by Bahaj and Reis (2022) and Cetorelli et al. (2020b), and echoes the theoretical mechanism in the former paper.

[15] In the above extension with dollar equity, this would in turn reduce the price of dollar equity.

The response to an increase in ω captures flight to safety episodes, as in early March 2020. An increase in the demand for safe dollar assets widens the liquidity premium and appreciates the dollar, following the existing literature; more novel, it increases the deviation from CIP provided $\lambda < 1$ because, in this case, the demand for safe dollar assets disproportionately rises in Foreign. The increased position of Foreign in safe dollar bonds increases its demand for hedging, widening the CIP deviation. We can also contrast the propagation of this shock in the presence of swap lines, as opposed to the case where they are absent. With swap lines, the same increase in the demand for safe dollar assets does not widen the CIP deviation and the dollar does not appreciate, as there is simply more usage of the swap line.

4 Conclusion

In this paper we have studied the high frequency effects of dollar swap lines on asset prices. We find that news about expanded dollar swap lines causes a reduction in liquidity premia, compression of deviations from CIP, and depreciation of the dollar. Equity prices rise and the VIX falls, while the response of long-term government bond prices is mixed. We argue that these asset pricing responses are qualitatively consistent with a model in which dollar swap lines increase the supply of safe dollar liquidity, and in which liquidity premia, CIP deviations, exchange rates, and other asset prices are jointly determined.

We expect that quantitatively accounting for the estimates of this paper using the model we have proposed requires additional features such as nominal rigidities and segmentation within each country. Such a framework may also be useful in accounting for unconditional comovements between liquidity premia, CIP deviations, and exchange rates uncovered in the literature. We leave these tasks for future work.

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Appendix for Online Publication

A Swap line announcements

In this section we outline the set of 21 swap line announcements from which we obtain our sample of eight announcements studied in the main text and in this appendix.

Table 4 summarizes the 15 announcements over the 2007-2010 period from Table 1 of Goldberg et al. (2011). We obtain the press release time from the Federal Reserve's website.[16] We also characterize simultaneous Federal Reserve news by reading the press releases and searching the Federal Reserve website for other press releases at the same time as the ones of interest. We highlight the six announcements without simultaneous news from the Federal Reserve, and with a posted press release time.

Table 5 summarizes six announcements from the 2020-2021 period.[17] We obtain these by manually reading the titles of all Federal Reserve press releases over these two years and identifying those referencing the swap lines, and we characterize the associated press release times and simultaneous Federal Reserve news as above. We highlight the two announcements without simultaneous news from the Federal Reserve, and with a posted press release time.

The resulting eight announcements form our sample of analysis in the main text and in this appendix.

B Measures of liquidity premia

In this section we present the measures of liquidity premia from Figure 1 of the paper, but over a longer sample period.

Figure 7 depicts these measures from January 1997 through June 2020. For readability, we plot the month-end values for each series. There is a striking comovement across these measures, suggesting they all capture the liquidity or safety of money-like

[16] In four cases, no press release time is provided.

[17] There is one announcement on March 31, 2020 pertaining to the Foreign and International Monetary Authorities (FIMA) repo facility which could have been added to this list. While this is not the same as the dollar swap lines, it is similar. However, the usage of the FIMA repo facility was negligible relative to the swap lines, so we exclude this announcement from the paper. We have conducted an intraday analysis for this announcement and find directionally similar, but smaller, effects on asset prices from this announcement versus the ones studied in the paper.

Date	Press release	Event	Simultaneous Federal Reserve news
12/12/07		Fed establishes 6-month swap lines with ECB and SNB	Establishment of TAF
3/11/08		Lines expanded	Establishment of TSLF
5/2/08		Lines expanded and agreement extended	Expansion of TAF and TSLF
7/30/08	8:45	Lines expanded	Expansions of PDCF, TAF, and TSLF
9/18/08	**3:00**	**Lines expanded and lines established with BOC, BOE, and BOJ**	
9/24/08	**1:00**	**Lines established with RBA, Danmarks NationalBank, Sveriges Riksbank, and Norges Bank**	
9/26/08	**2:00**	**Lines expanded**	
9/29/08	10:00	Lines expanded and agreements extended	Expansion of TAF
10/13/08	**2:00**	**Lines expanded**	
10/14/08		Lines expanded	
10/28/08	**17:00**	**Lines established with RBNZ**	
10/29/08	**15:30**	**Lines established with Banco Central do Brasil, Bank of Korea, Banco de Mexico, and Monetary Authority of Singapore**	
2/3/09	10:00	Agreements extended	Extension of AMLF, CPFF, MMIFF, PDCF, and TSLF
4/6/09	10:00	Arrangement to provide foreign currency liquidity to U.S. institutions	TAF auction
6/25/09	12:00	Agreements extended	Extension of AMLF, CPFF, PDCF, and TSLF

Table 4: swap line announcements during Great Recession

Notes: press release times in EDT. Bold denotes announcements studied in this appendix.

Date	Press release	Event	Simultaneous Federal Reserve news
3/15/20	17:00	Lower pricing and longer maturities on standing swap lines	Releases of FOMC statement and actions to support flow of credit to households and businesses
3/19/20	**9:00**	**Temporary lines established with RBA, Banco Central do Brasil, Danmarks NationalBank, Bank of Korea, Banco de Mexico, Norges Bank, RBNZ, Monetary Authority of Singapore, and Sveriges Riksbank**	
3/20/20	**10:00**	**Increased frequency of standing swap lines to daily**	
7/29/20	14:00	Agreements extended	Release of FOMC statement
12/16/20	14:00	Agreements extended	Release of FOMC statement
7/16/21	14:00	Agreements extended	Release of FOMC statement

Table 5: swap line announcements during pandemic

Notes: press release times in EDT. Bold denotes announcements studied in main text and this appendix.

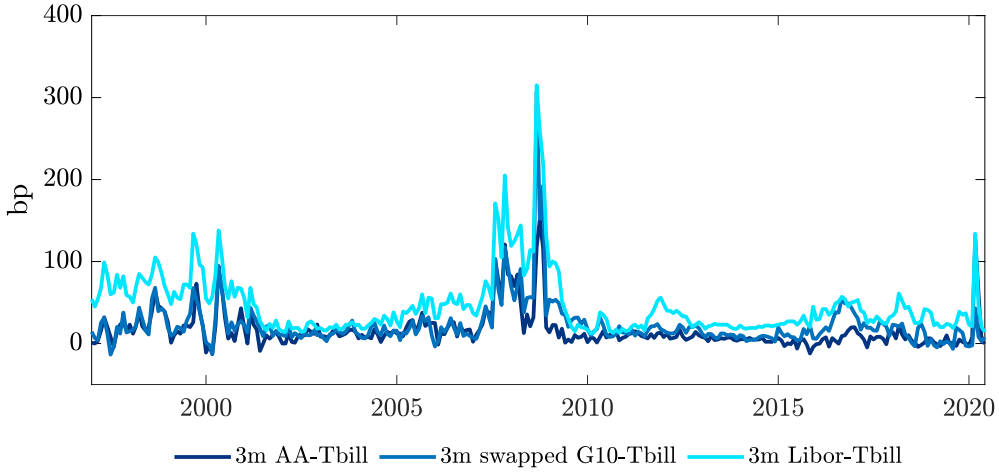


Figure 7: measures of liquidity premia

dollar assets such as Treasury bills. The Libor/Treasury bill spread is generally higher than the others, consistent with it also reflecting counterparty risk among banks as the literature has documented.

C Additional evidence on 2020 announcements

In this section we present additional evidence on the effects of the March 2020 swap line announcements studied in the main text.

Figures 8-11 present trading volume (for futures) and number of quotes (for forwards) by one-minute bar for the securities studied in Figures 2-5 in the main text. Trading in Fed funds futures is more sporadic than the others, but in all cases there is nonzero volume around the announcements.

Table 6 provides additional high frequency responses supplementing those in Tables 1 and 2 in the main text. The first panel reports the responses of three-month CIP deviations using OIS rates. There are only sufficiently frequent intraday quotes of OIS rates for four currencies to estimate these, and of these it is evident from Figures 12 and 13 which follow that quotes in Canadian dollar and New Zealand dollar OIS rates are quite thin around the announcements. For the euro and British pound, however, the responses of the three-month CIP deviations are essentially identical to those of the three-month forward premiums in Table 2. Even for the Canadian dollar and New Zealand dollar, the response of forward premiums and CIP deviations are

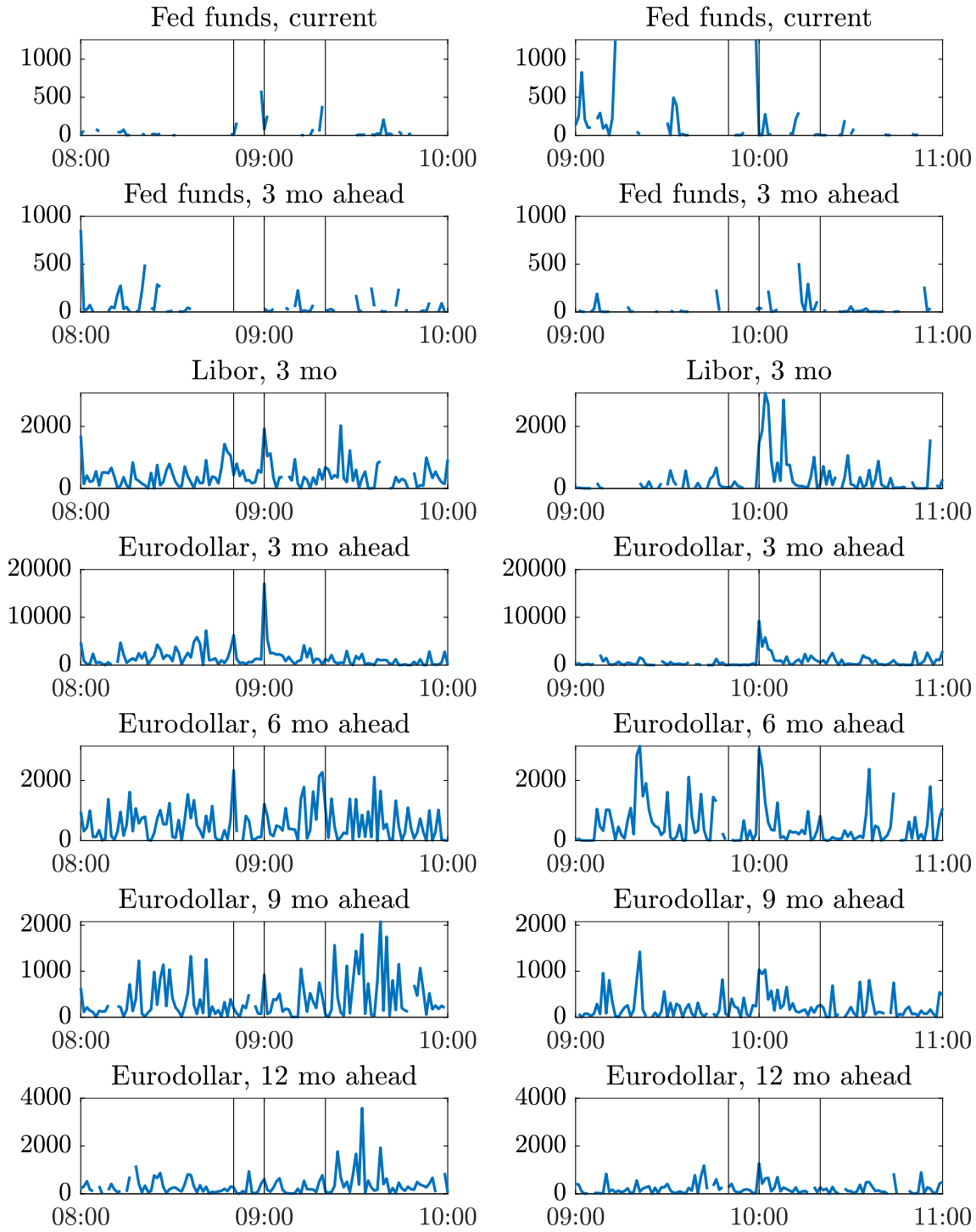


Figure 8: interest rate futures volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

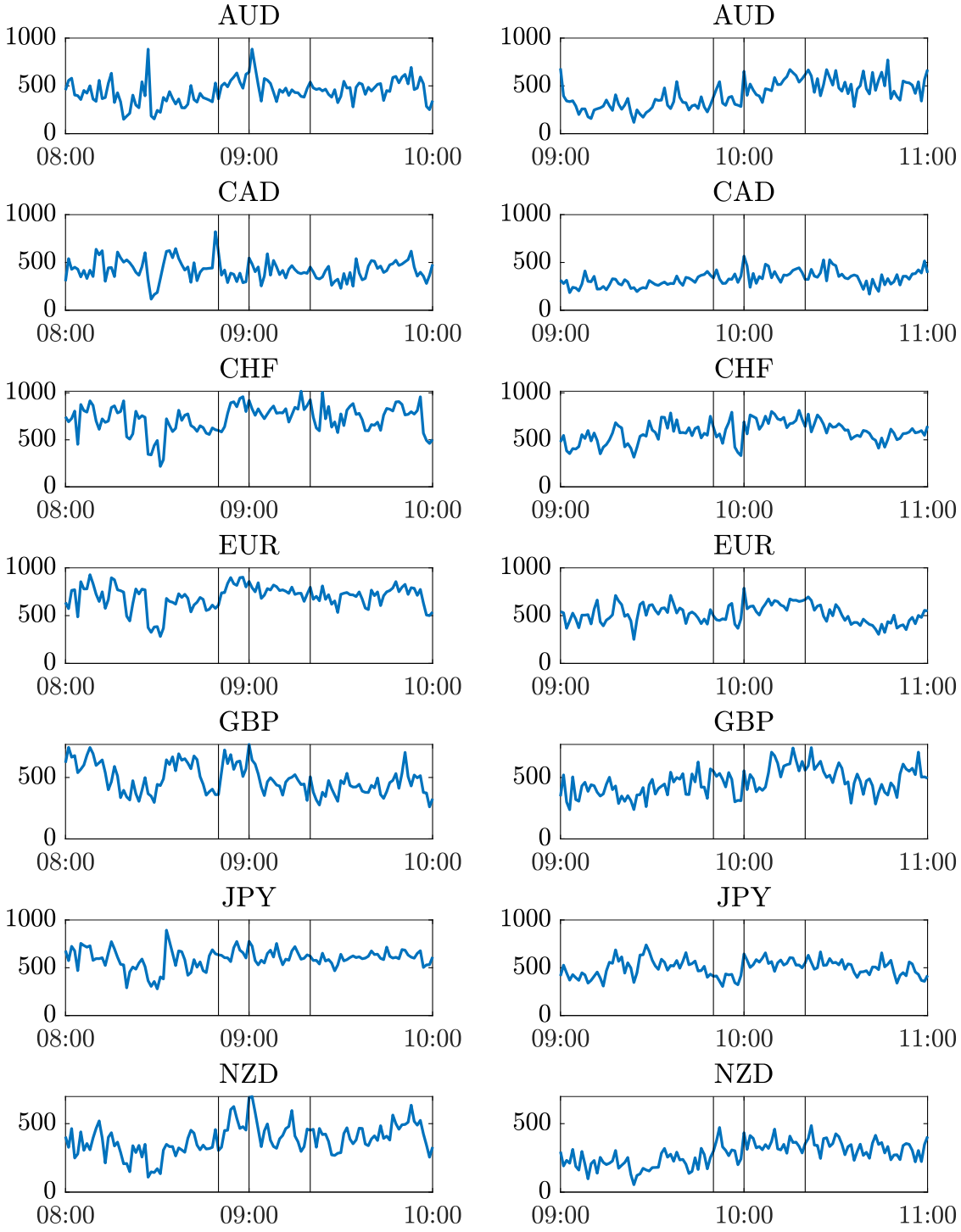


Figure 9: spot exchange rates volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

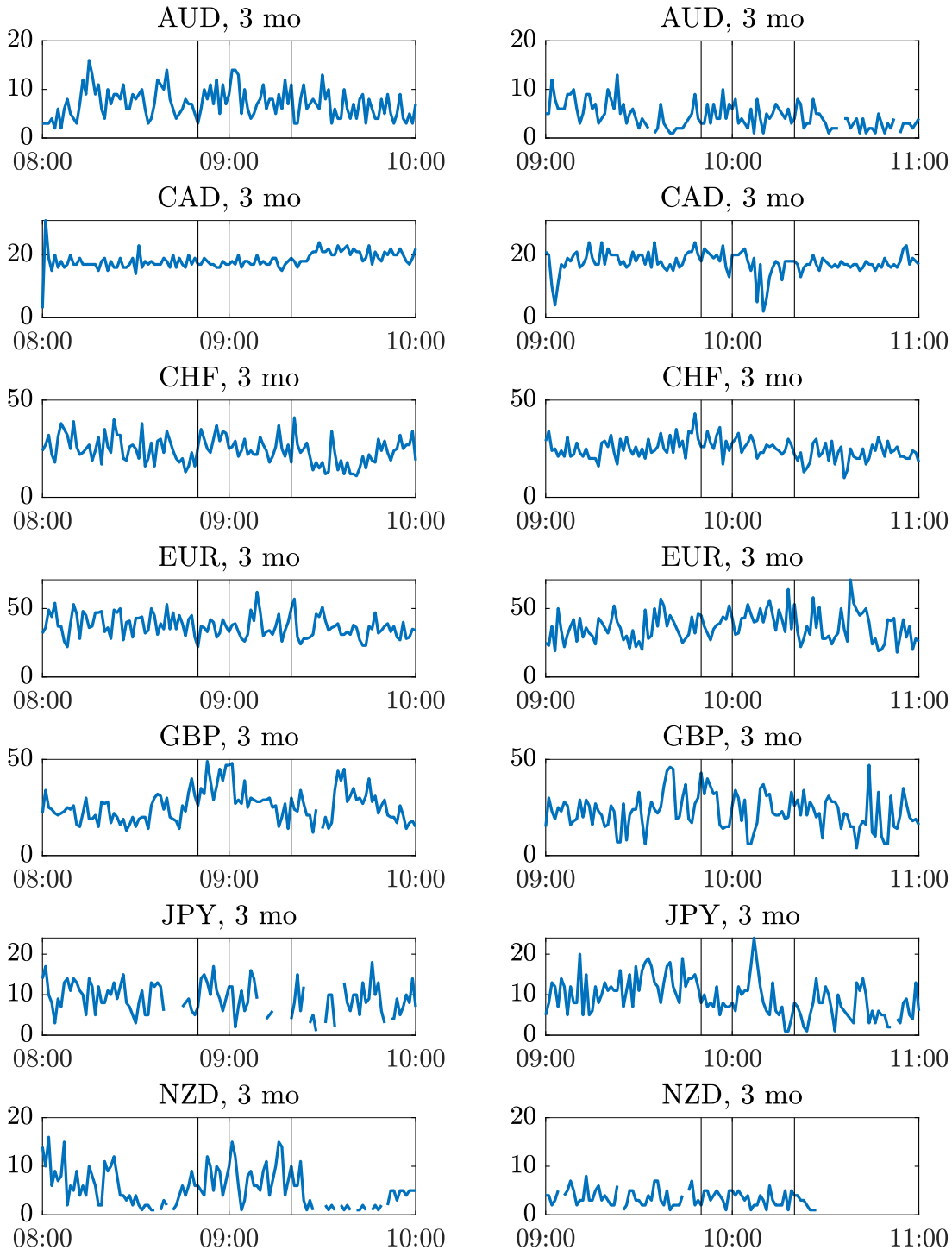


Figure 10: forward volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict average number of bids and asks by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

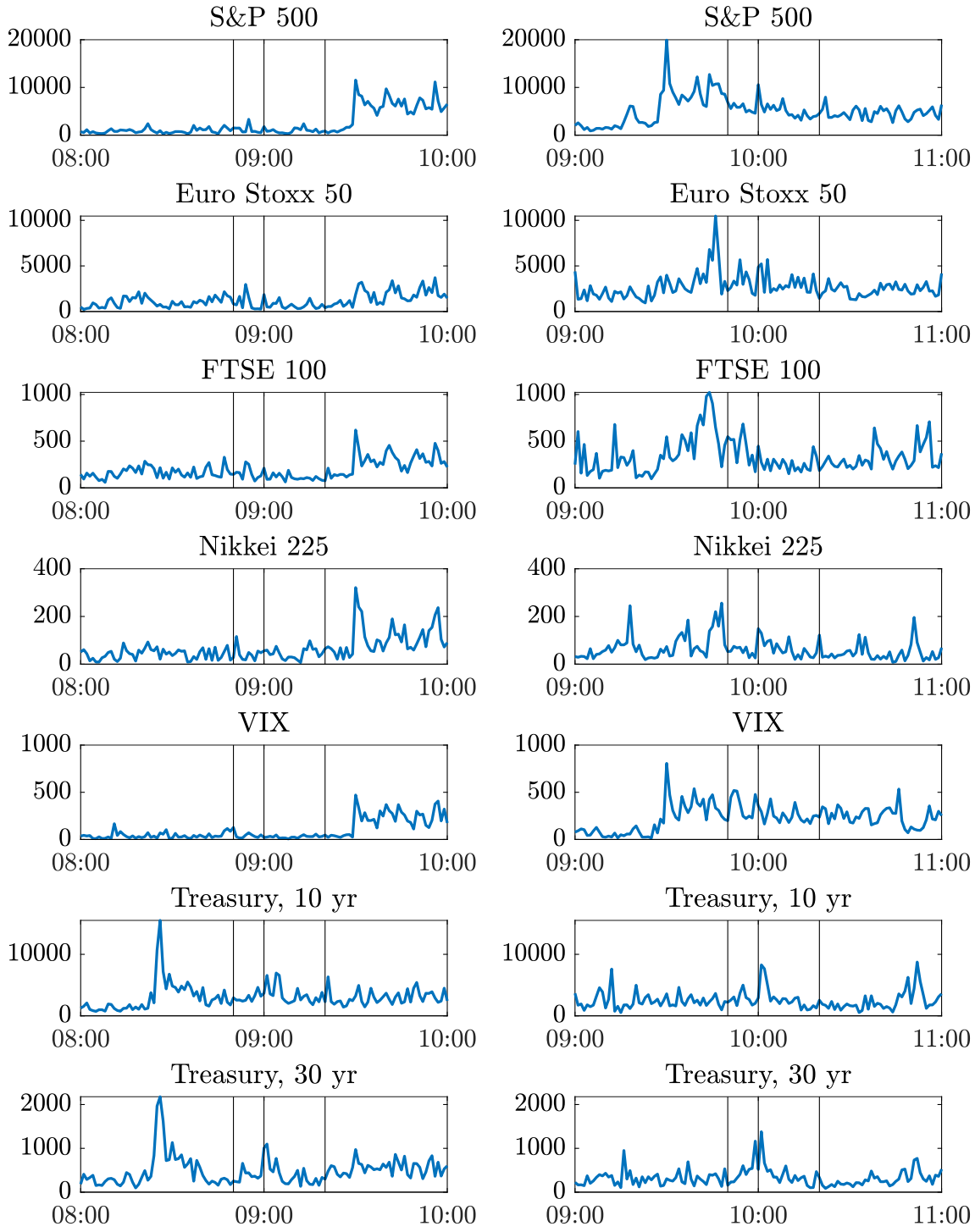


Figure 11: equity and bond futures volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

within a few basis points of each other.

The second panel of Table 6 reports the responses of emerging market currencies and equities. These responses are consistent with the G10 currencies and equities responses in Tables 1 and 2: the dollar depreciates and equities rise, in the former case by a statistically significant amount. Figures 14 and 15 depict the associated responses and trading volume; as is evident, trading in the emerging market contracts is more thin than for the G10 countries.

Finally, the third panel of Table 6 reports additional responses of bond prices. As in the case of the bonds studied in Table 2, some bond prices rise, some fall, and the overall responses are muted. Figures 16 and 17 depict the responses and volume.

Tables 7-9 are analogs to Tables 1, 2, and 6 except using one day changes in each asset price. In particular, we define the one day change as the log closing price on the announcement day less the log closing price on the prior trading day, multiplied by 10000. Using the cumulative two-day change in these asset prices, the dollar appreciated by 66*bp*, the S&P 500 futures price fell by 486*bp*, and 30-year Treasury bond futures price rose by 488*bp*, consistent with the flight to safety during this period. We further see that the interest rate responses are now inconsistent across announcements, some foreign currencies appreciate versus the dollar while others depreciate, and the CIP deviations widen on average on March 19. Overall, this underscores the importance of focusing on intraday windows to identify the effects from dollar supply alone on our asset prices of interest.

D Additional evidence on 2008 announcements

In this section we present additional evidence on the effects of the September-October 2008 swap line announcements identified in section A of this appendix.

Figure 18 is the analog of Figure 1 over the September-November 2008 period. Again we see that the use of swap lines is associated with a decline in these measures of liquidity premia from early October onwards. The rise in these spreads through September is consistent with an intensifying flight to safety over this period, and again underscores the value of high frequency analysis for our outcomes of interest. We further note that, unlike the March 2020 announcements studied in the main text, three of the six announcements during this period occurred when a substantial amount of the swap line usage had already occurred.

	3/19/20	3/20/20	Sum
CIP deviations			
AUD, 3 mo	.	.	.
CAD, 3 mo	2	8	9***
CHF, 3 mo	.	.	.
EUR, 3 mo	6	43	50***
GBP, 3 mo	-2	19	18***
JPY, 3 mo	.	.	.
NZD, 3 mo	-1	-5	-6
Average, 3 mo	1	16	18
*EM currency and equity futures**			
BRL	-57	-9	-66
MXN	-46	-54	-100
RUB	-173	-47	-220**
ZAR	-31	-51	-82
Average of EM currencies	-77	-40	-117**
MSCI EM Equity Index	109	25	134
Additional bond futures			
Treasury, 2 yr	3	3	6
Treasury, 5 yr	13	2	15
Gilt, 10 yr	18	-42	-23
Euro shatz, 1.75-2.25 yr	-1	1	-0
Euro bobl, 4.5-5.5 yr	-3	1	-2
Euro bund, 8.5-10.5 yr	-1	-4	-6
Euro buxl, 24.0-35.0 yr	15	4	19

Table 6: additional high frequency responses

Notes: responses are defined as the log open price of the first one-minute bar with positive trading volume beginning 20 minutes after the press release time, less the log close price of the last one-minute bar with positive trading volume ending 10 minutes before the press release time, multiplied by 10000 (thus reported in *bp*). Response is missing (denoted .) if there is no trading volume in 10-20 minutes prior to the press release time or 20-40 minutes after the press release time. ***, **, and * denote statistical significance of cumulative responses at 10%, 5%, and 1% levels, respectively.

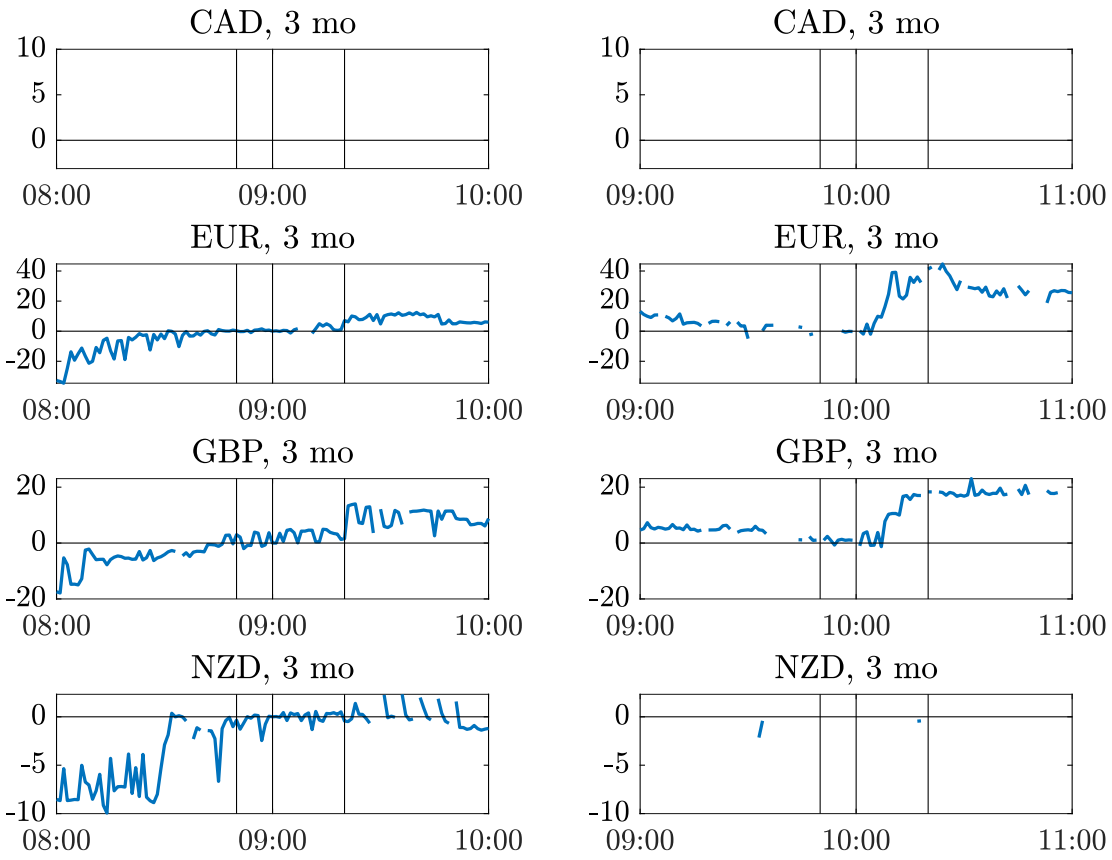


Figure 12: CIP deviations on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict CIP deviation at open by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

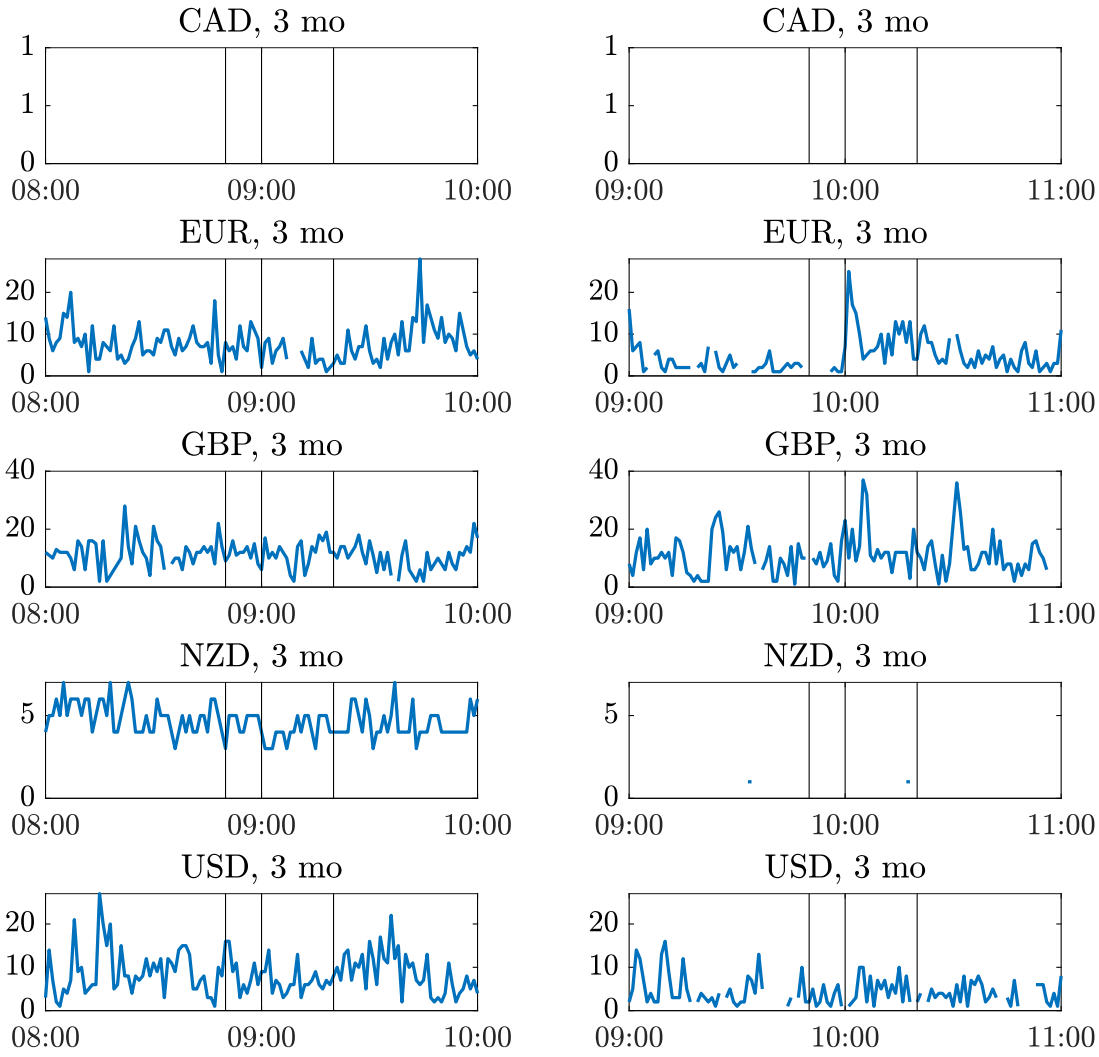


Figure 13: OIS volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict average number of bid and ask quotes by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

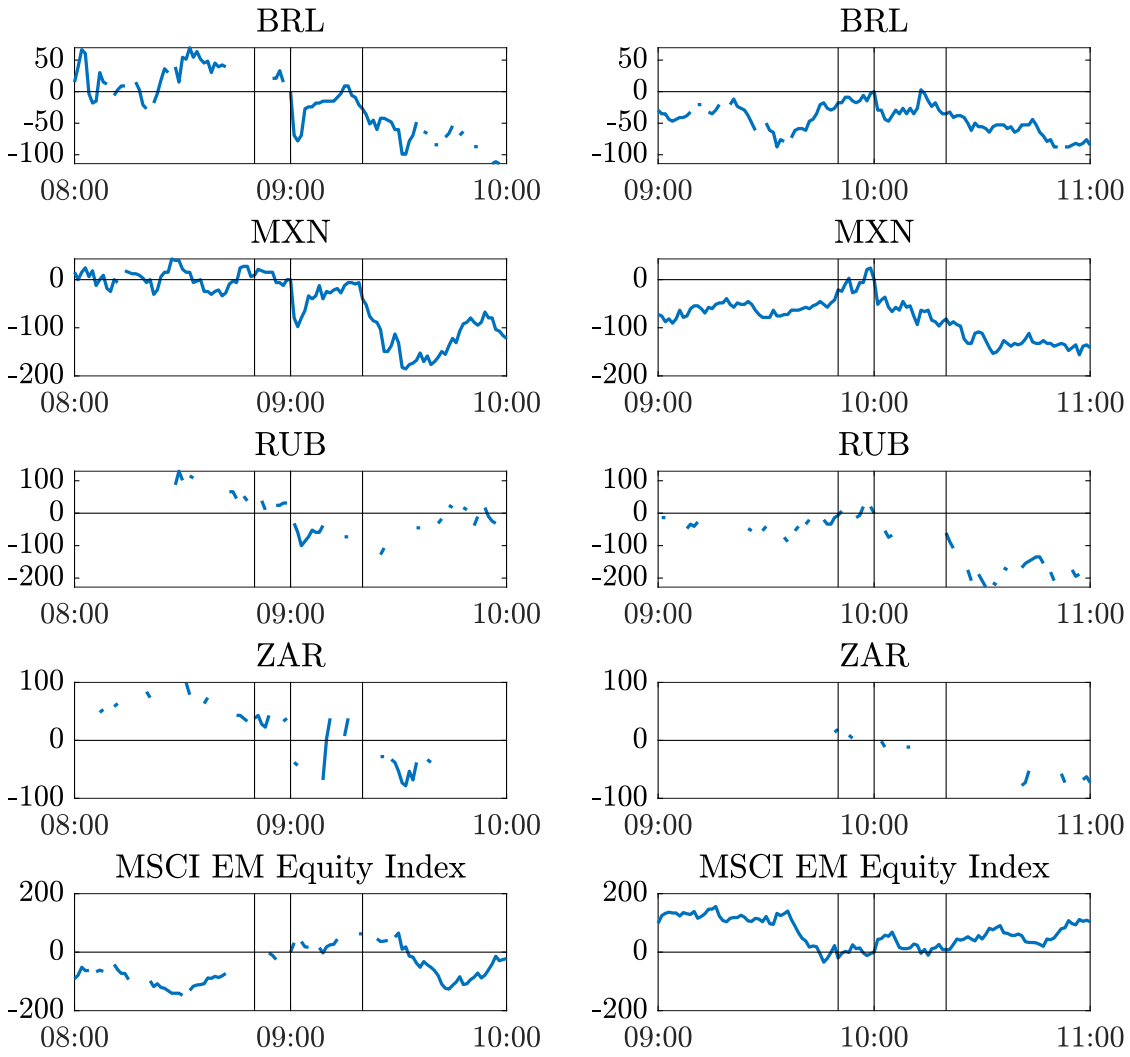


Figure 14: EM currency and equity futures on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict log open price by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

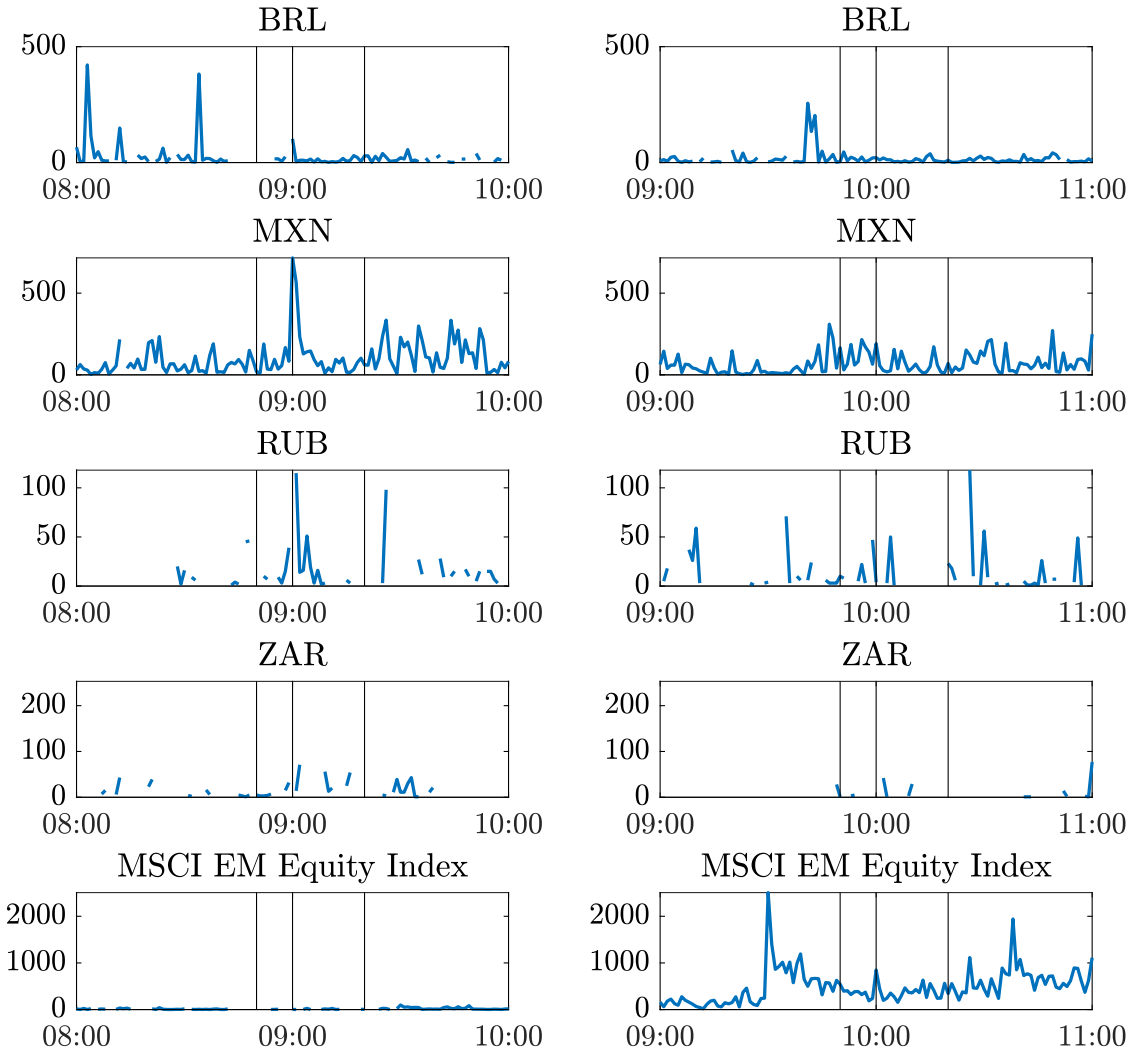


Figure 15: EM currency and equity futures volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

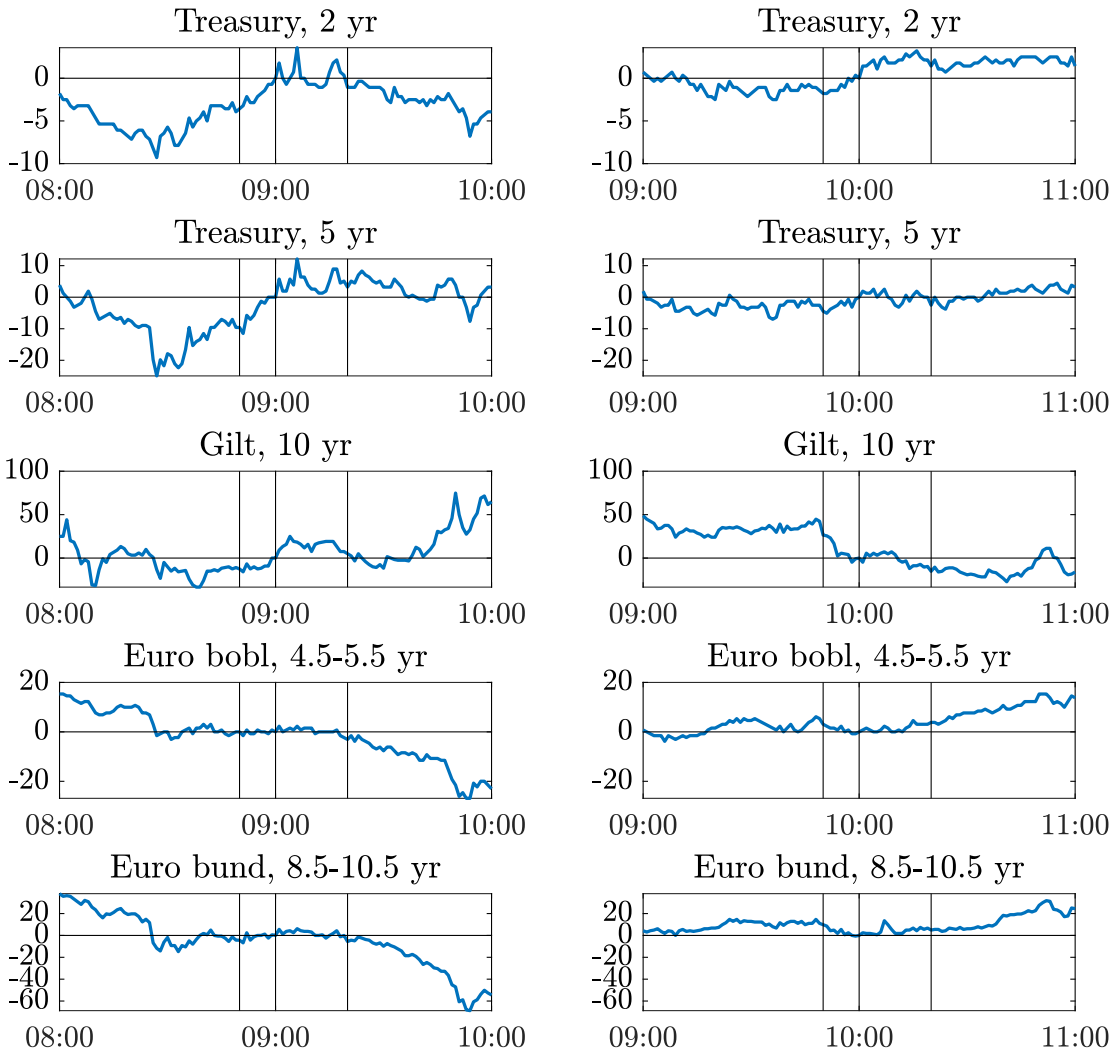


Figure 16: additional bond futures on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict log open price by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

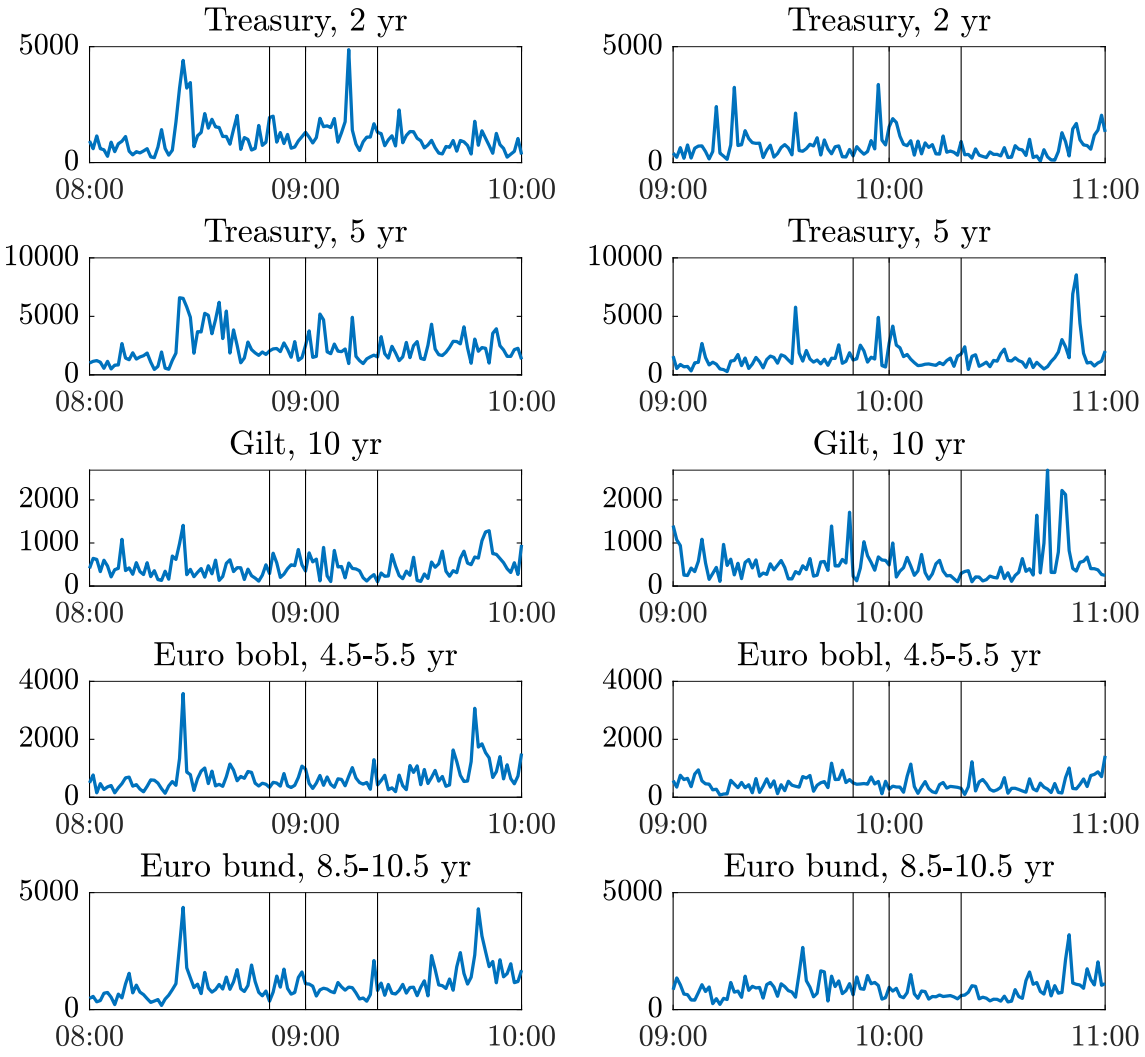


Figure 17: additional bond futures volume on 3/19/20 (L) and 3/20/20 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

	3/19/20	3/20/20	Sum
Interest rate futures			
Fed funds, current contract	1	-6	-5
Fed funds, 3 mo ahead	1	-1	1
Libor, 3 mo	10	-21	-10
Eurodollar, 3 mo ahead	12	-11	1
Eurodollar, 6 mo ahead	3	-8	-5
Eurodollar, 9 mo ahead	1	-8	-8
Eurodollar, 12 mo ahead	1	-10	-9
Spot exchange rates			
AUD	50	-109	-59
CAD	-1	-123	-123
CHF	183	-5	179
EUR	205	-8	198
GBP	114	-138	-24
JPY	245	8	252
NZD	602	-565	36
Average	200	-134	66

Table 7: one day responses (1/3)

Notes: responses are defined as the log close price as of announcement day, less the log close price as of the trading day prior to announcement, multiplied by 10000 (thus reported in *bp*). Interest rate responses multiplied by minus one, so these correspond to responses of yields.

	3/19/20	3/20/20	Sum
Forward premiums			
AUD, 3 mo	-7	11	4
CAD, 3 mo	-2	17	15
CHF, 3 mo	1	47	48
EUR, 3 mo	-2	46	44
GBP, 3 mo	-24	48	24
JPY, 3 mo	-60	70	10
NZD, 3 mo	28	-37	-9
Average, 3 mo	-9	29	19
Equity index futures			
S&P 500	-53	-434	-486
Euro Stoxx 50	316	366	682
FTSE 100	180	-63	117
Nikkei 225	302	22	324
VIX	-333	-396	-729
Bond futures			
Treasury, 10 yr	87	115	203
Treasury, 30 yr	287	201	488

Table 8: one day responses (2/3)

Notes: responses are defined as the log close price as of announcement day, less the log close price as of the trading day prior to announcement, multiplied by 10000 (thus reported in *bp*).

	3/19/20	3/20/20	Sum
CIP deviations			
AUD, 3 mo	-8	10	2
CAD, 3 mo	-0	14	14
CHF, 3 mo	-15	43	29
EUR, 3 mo	-0	44	43
GBP, 3 mo	-16	46	31
JPY, 3 mo	-58	.	.
NZD, 3 mo	32	-40	-8
Average, 3 mo	-9	20	10
EM currency and equity futures			
BRL	-212	-169	-381
MXN	195	-69	127
RUB	-483	232	-251
ZAR	197	-5	192
Average of EM currencies	-76	-3	-78
MSCI EM Equity Index	61	109	170
Additional bond futures			
Treasury, 2 yr	22	6	28
Treasury, 5 yr	62	57	120
Gilt, 10 yr	-37	258	222
Euro shatz, 1.75-2.25 yr	-26	5	-20
Euro bobl, 4.5-5.5 yr	-54	63	9
Euro bund, 8.5-10.5 yr	-52	152	99
Euro buxl, 24.0-35.0 yr	-146	344	198

Table 9: one day responses (3/3)

Notes: responses are defined as the log close price as of the announcement day, less the log close price as of the trading day prior to announcement, multiplied by 10000 (thus reported in *bp*).

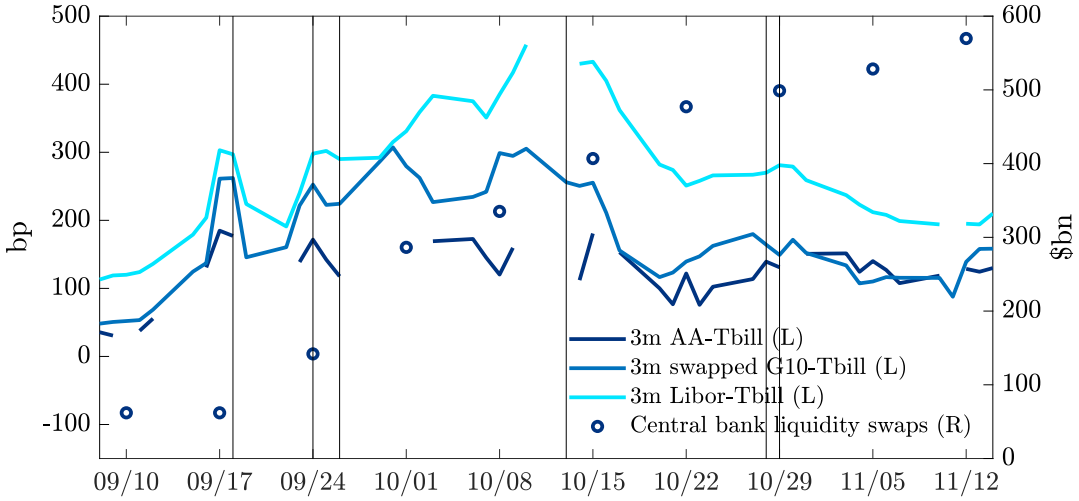


Figure 18: swap line usage and liquidity premia in 2008

Notes: vertical lines denote announcement dates.

Tables 10-12 report the high frequency responses to these six announcements.[18] Relative to Tables 1, 2, and 6, there are many more missing observations. This reflects the absence of sufficient trading/quote volume around these announcements, in part because several of these occurred overnight in the United States. Where data does exist, the results are broadly in line with those for the March 2020 announcements. In particular, these announcements generally caused a reduction in Eurodollar rates consistent with a reduction in liquidity premia; a depreciation of the dollar (except against the yen); a rise in forward premiums; an increase in the S&P 500; and a mixed and muted response of Treasury bonds. The dollar interestingly appreciated versus other currencies around the September 18, 2008 announcement, even though forward premiums still rose.

Figures 19-34 depict the prices and associated trading/quote volumes around these announcements. The thinness of volumes is again evident versus the March 2020 announcements. However, where data around the announcements does exist, in many cases we see sharp responses upon the announcement.

[18]Because FirstRate Data only reports intraday spot rates from 2010 onwards, we use Refinitiv as the source for spot exchange rates during this period. As with the other Refinitiv data, this means we define the spot exchange rate as the average of bid and ask quotes.

	9/18	9/24	9/26	10/13	10/28	10/29
Interest rate futures						
Fed funds, current contract	1	.	.	.	.	.
Fed funds, 3 mo ahead	3	.	.	.	.	-1
Libor, 3 mo	-1	.	.	.	.	.
Eurodollar, 3 mo ahead	-17	-7	-6	.	.	.
Eurodollar, 6 mo ahead	-10	-3	-2	.	.	.
Eurodollar, 9 mo ahead	-2	-1	-1	.	.	.
Eurodollar, 12 mo ahead	3	2	0	.	.	.
Spot exchange rates						
AUD	-3	-23	-2	-148	-70	-73
CAD	-4	-9	3	-28	5	-41
CHF	49	-2	7	18	-7	-30
EUR	27	-3	0	-52	-13	-15
GBP	31	-5	11	-60	-1	-8
JPY	64	-0	14	21	87	6
NZD	10	-16	-9	-113	-54	-21
Average	25	-8	4	-52	-8	-26

Table 10: high frequency responses in 2008

Notes: responses are defined as the log open price of the first one-minute bar with positive trading volume beginning 20 minutes after the press release time, less the log close price of the last one-minute bar with positive trading volume ending 10 minutes before the press release time, multiplied by 10000 (thus reported in *bp*). Interest rate responses multiplied by minus one, so these correspond to responses of yields. Response is missing (denoted .) if there is no trading volume in 10-20 minutes prior to the press release time or 20-40 minutes after the press release time.

	9/18	9/24	9/26	10/13	10/28	10/29
Forward premiums						
AUD, 3 mo	-0	-0	0	0	0	0
CAD, 3 mo	.	-1	3	0	-3	-4
CHF, 3 mo	27	-0	-0	4	7	0
EUR, 3 mo	71	-5	-7	-0	2	-1
GBP, 3 mo	.	0	-2	.	-0	-5
JPY, 3 mo	95	19	-2	9	-3	1
NZD, 3 mo	15	-15	2	-3	41	14
Average, 3 mo	42	-0	-1	2	6	1
Equity index futures						
S&P 500	27	5	15	16	62	79
Euro Stoxx 50	40	.	.	.	.	238
FTSE 100	.	.	.	.	.	228
Nikkei 225	.	.	.	.	.	217
VIX	.	.	.	.	.	-37
Bond futures						
Treasury, 10 yr	-36	-8	-10	20	.	20
Treasury, 30 yr	-35	-8	-14	32	.	49

Table 11: high frequency responses in 2008

Notes: responses are defined as the log open price of the first one-minute bar with positive trading volume beginning 20 minutes after the press release time, less the log close price of the last one-minute bar with positive trading volume ending 10 minutes before the press release time, multiplied by 10000 (thus reported in *bp*). Response is missing (denoted .) if there is no trading volume in 10-20 minutes prior to the press release time or 20-40 minutes after the press release time.

	9/18	9/24	9/26	10/13	10/28	10/29
CIP deviations						
AUD, 3 mo	.	.	.	.	.	.
CAD, 3 mo	.	.	.	.	.	.
CHF, 3 mo	.	.	.	.	.	.
EUR, 3 mo	73	.	-13	.	.	.
GBP, 3 mo	.	.	-5	.	.	.
JPY, 3 mo	.	.	.	.	.	.
NZD, 3 mo	.	.	.	.	.	.
Average, 3 mo	73	.	-9	.	.	.
EM currency and equity futures						
BRL	.	.	.	.	.	.
MXN	.	.	.	.	.	-345
RUB	.	.	.	.	.	.
ZAR	.	.	.	.	.	.
Average of EM currencies	.	.	.	.	.	-345
MSCI EM Equity Index	.	.	.	.	.	.
Additional bond futures						
Treasury, 2 yr	-12	-2	-3	1	.	3
Treasury, 5 yr	-27	-4	-7	7	.	17
Gilt, 10 yr	.	.	.	.	.	.
Euro shatz, 1.75-2.25 yr	-13	.	.	.	.	-2
Euro bobl, 4.5-5.5 yr	-18	.	.	.	.	-2
Euro bund, 8.5-10.5 yr	-14	.	.	.	.	1
Euro buxl, 24.0-35.0 yr	10	.	.	.	.	.

Table 12: additional high frequency responses in 2008

Notes: responses are defined as the log open price of the first one-minute bar with positive trading volume beginning 20 minutes after the press release time, less the log close price of the last one-minute bar with positive trading volume ending 10 minutes before the press release time, multiplied by 10000 (thus reported in *bp*). Response is missing (denoted .) if there is no trading volume in 10-20 minutes prior to the press release time or 20-40 minutes after the press release time.

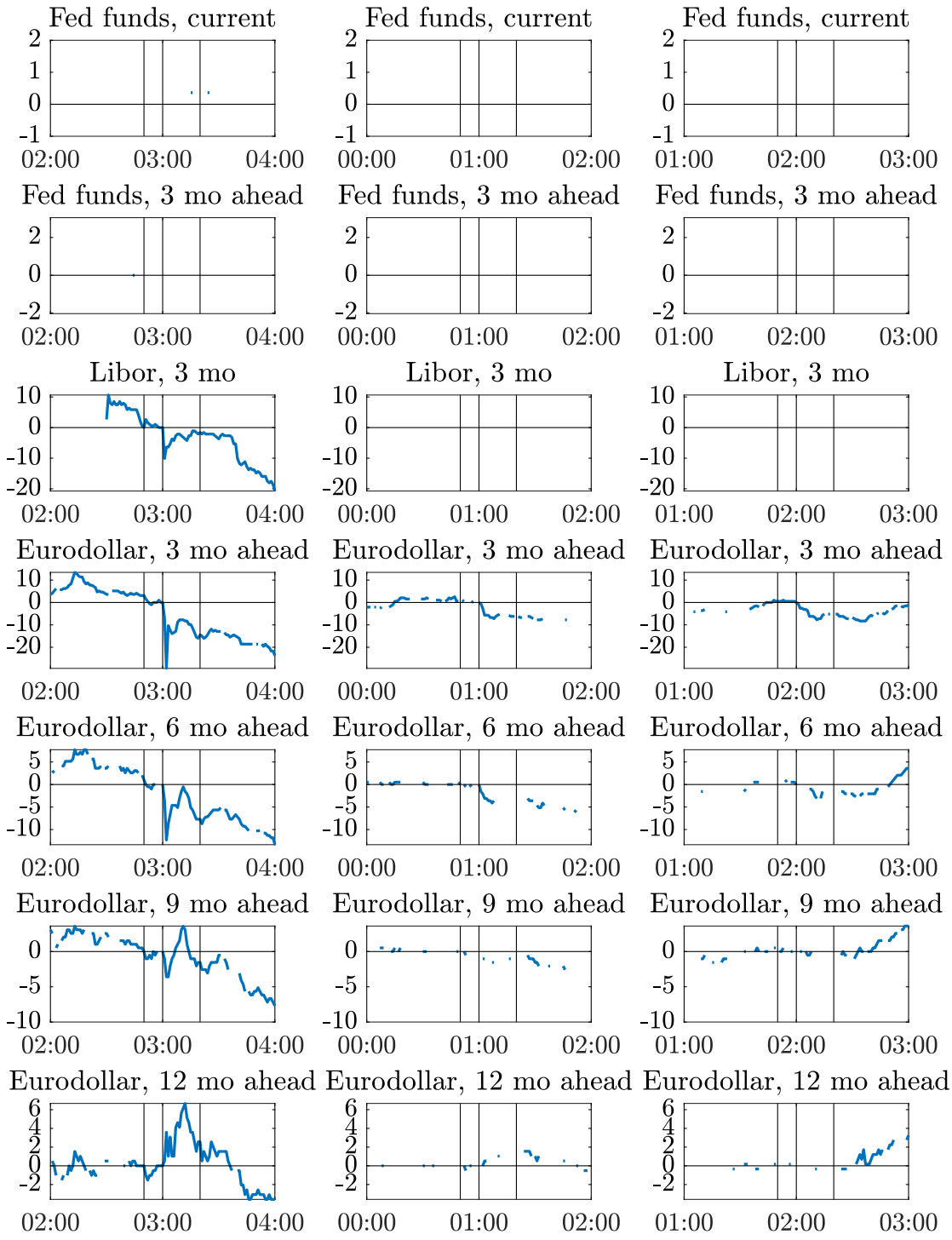


Figure 19: interest rate futures on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict log open price (for S&P 500 future) and −1 times log open price (for bond futures) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

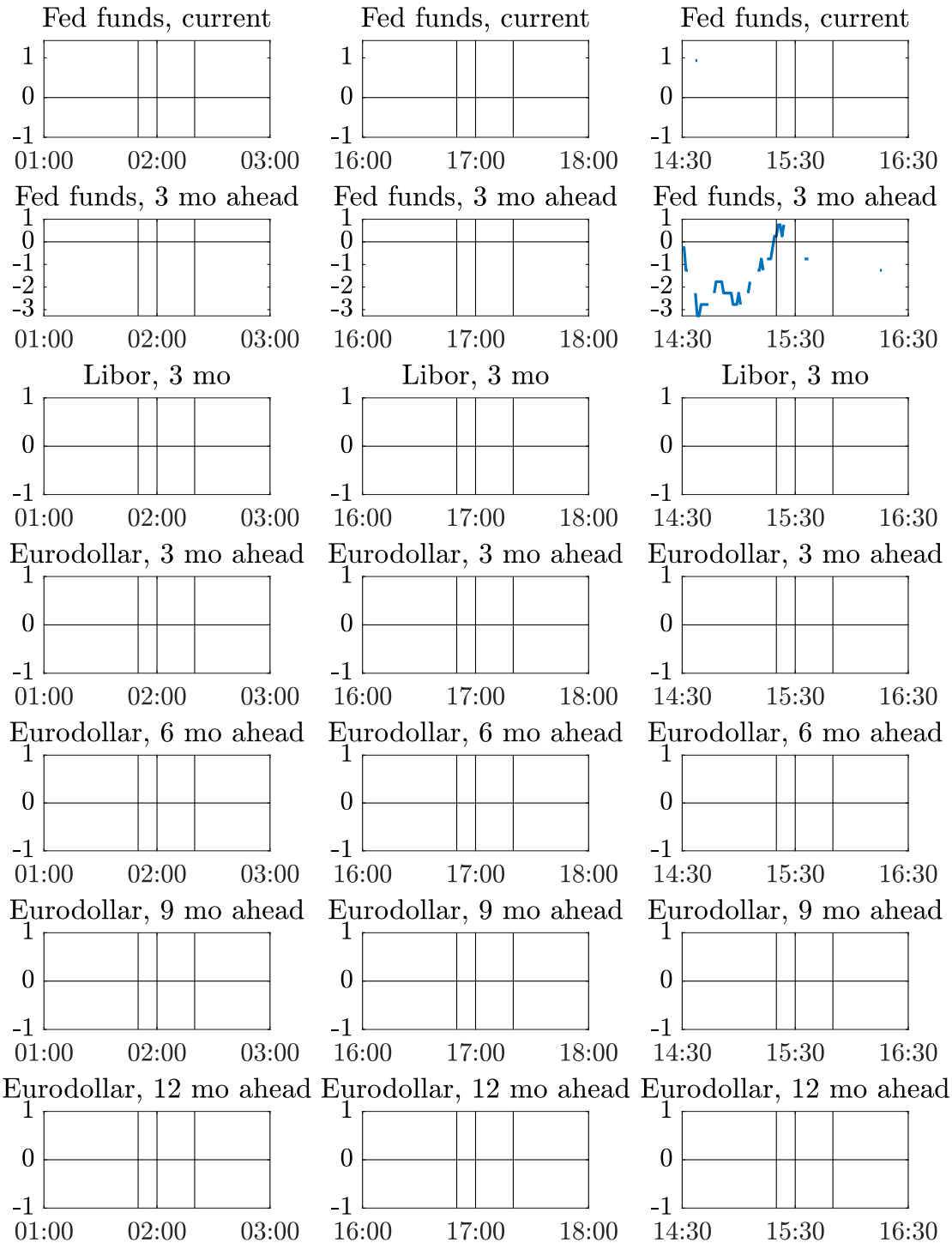


Figure 20: interest rate futures on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict log open price (for S&P 500 future) and −1 times log open price (for bond futures) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

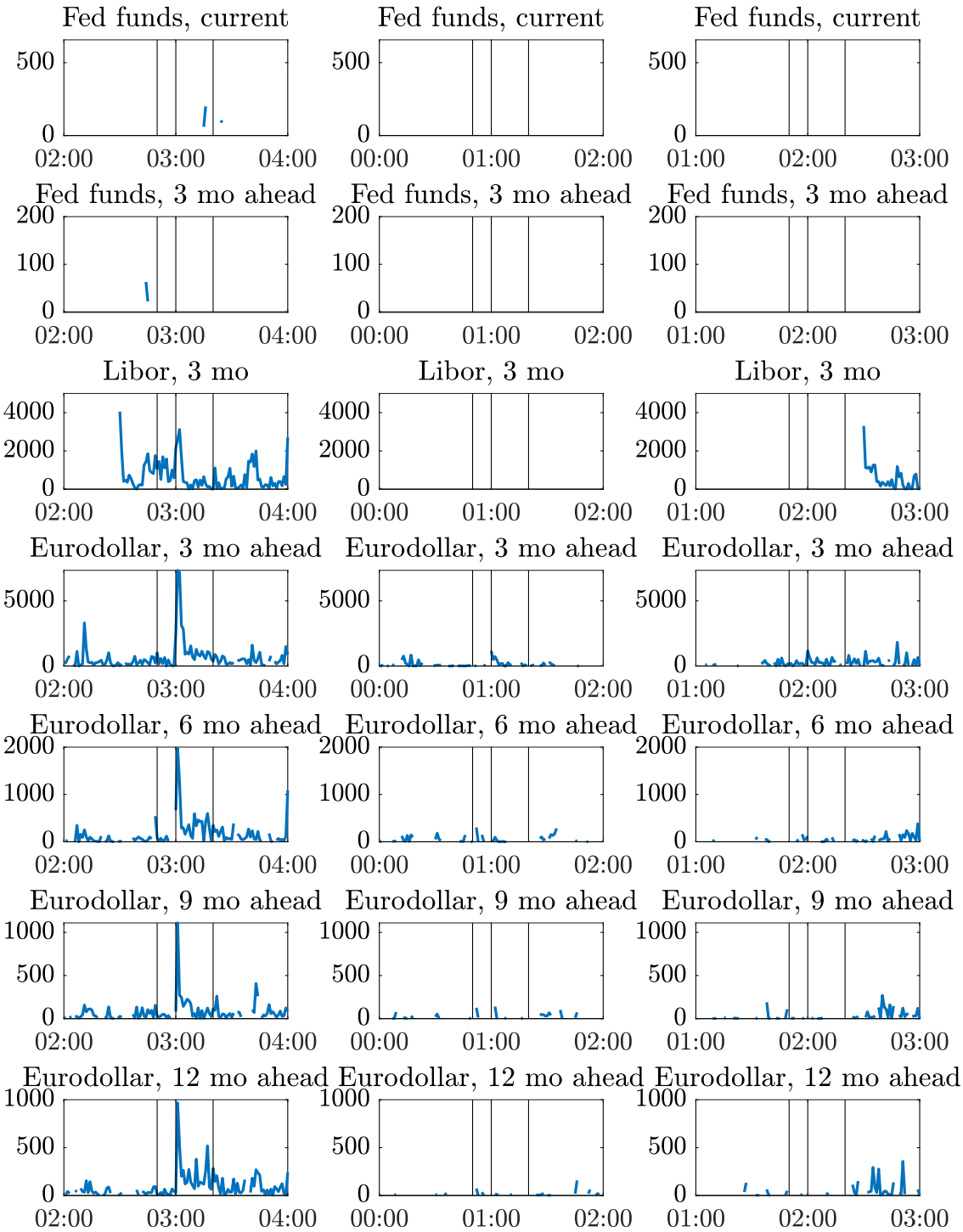


Figure 21: interest rate futures volume on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

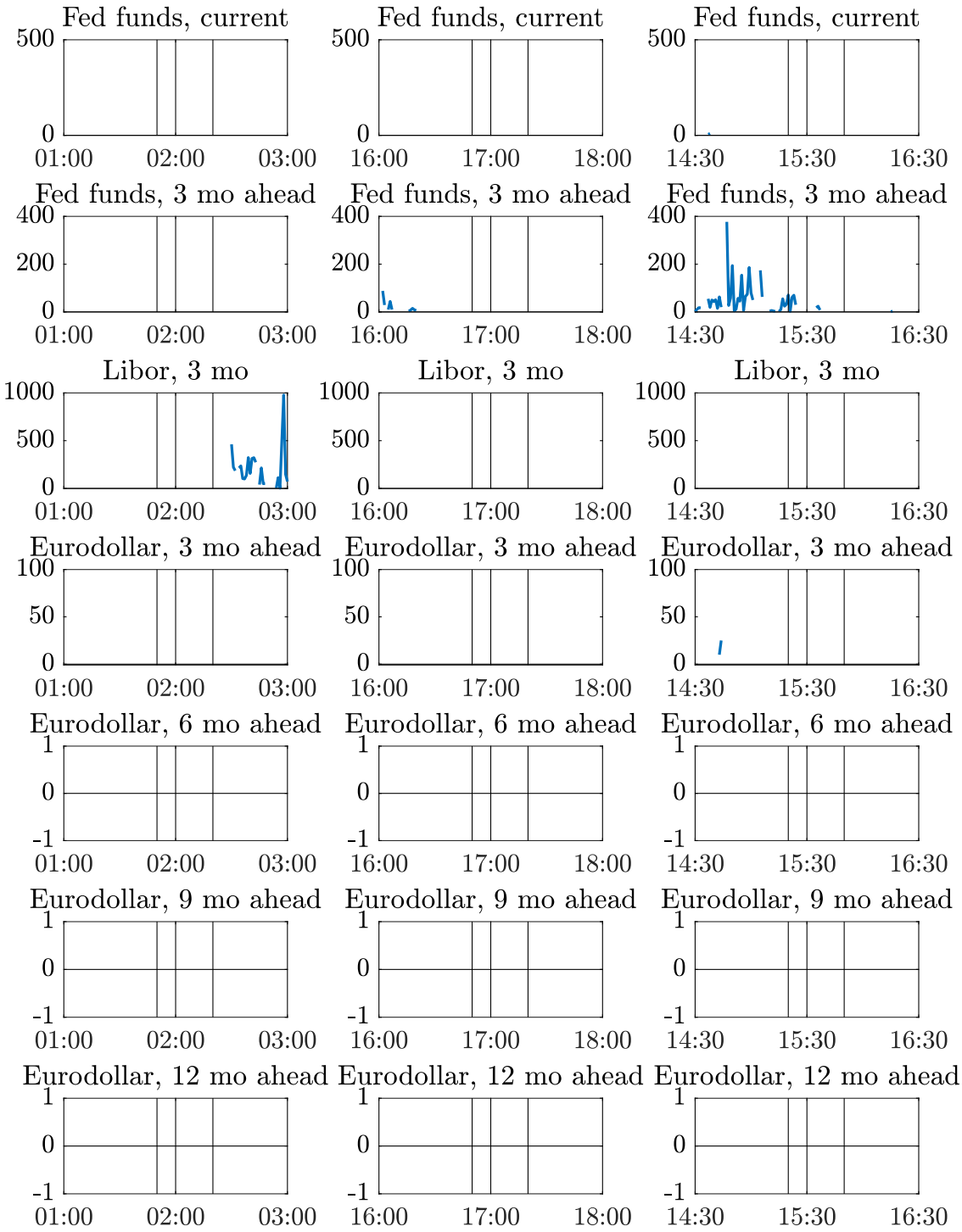


Figure 22: interest rate futures volume on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

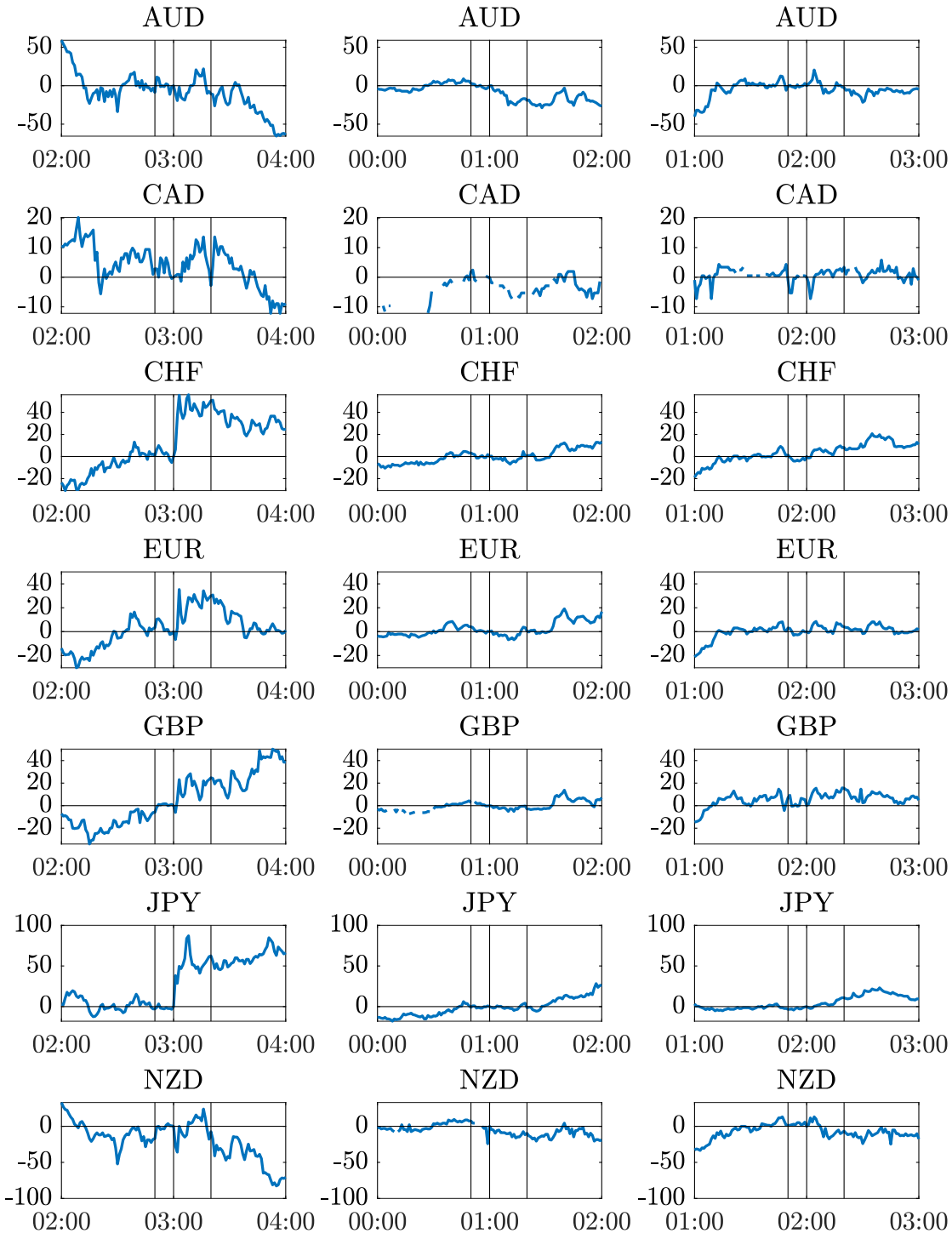


Figure 23: spot exchange rates on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict log open price (foreign per dollar) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

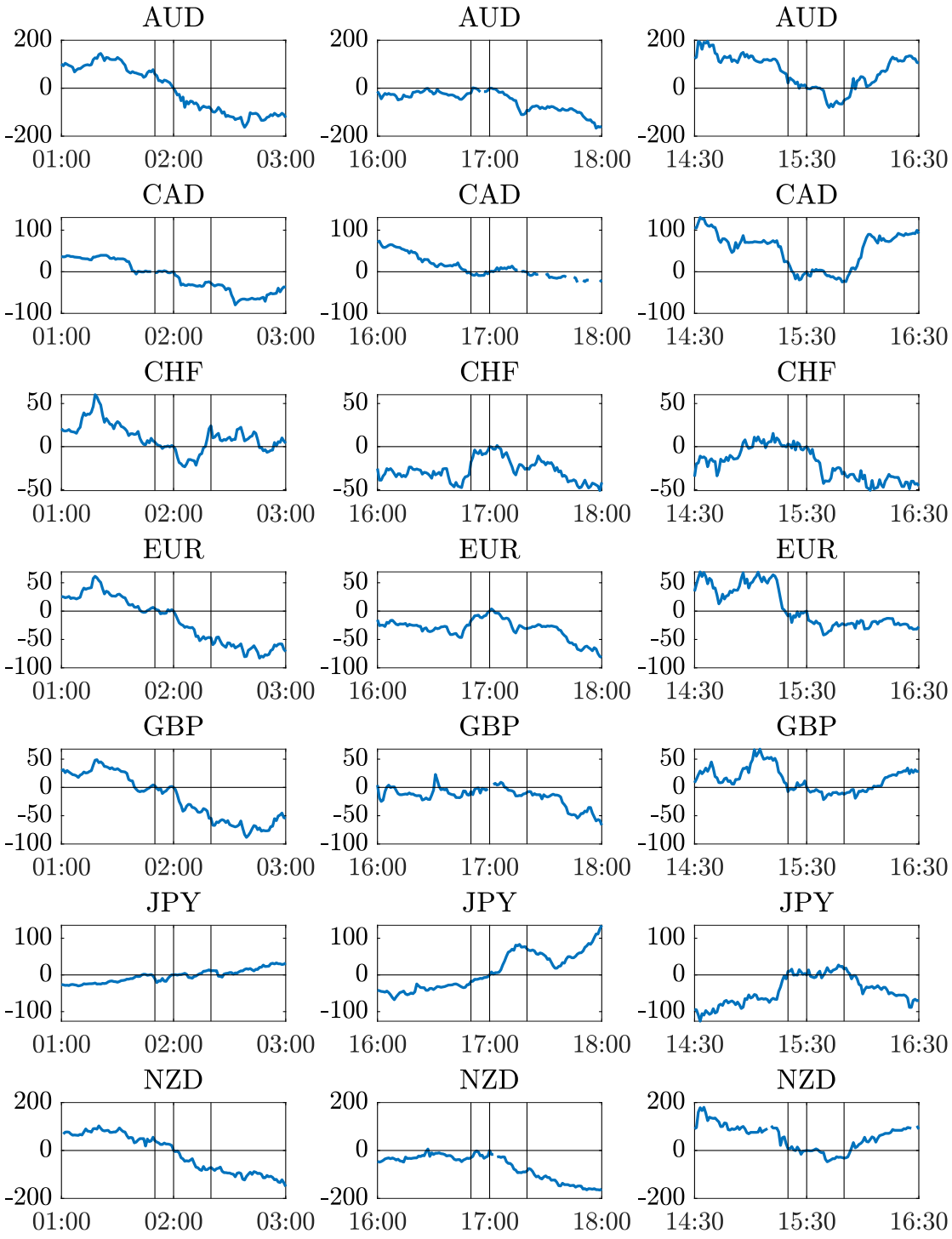


Figure 24: spot exchange rates on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict log open price (foreign per dollar) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

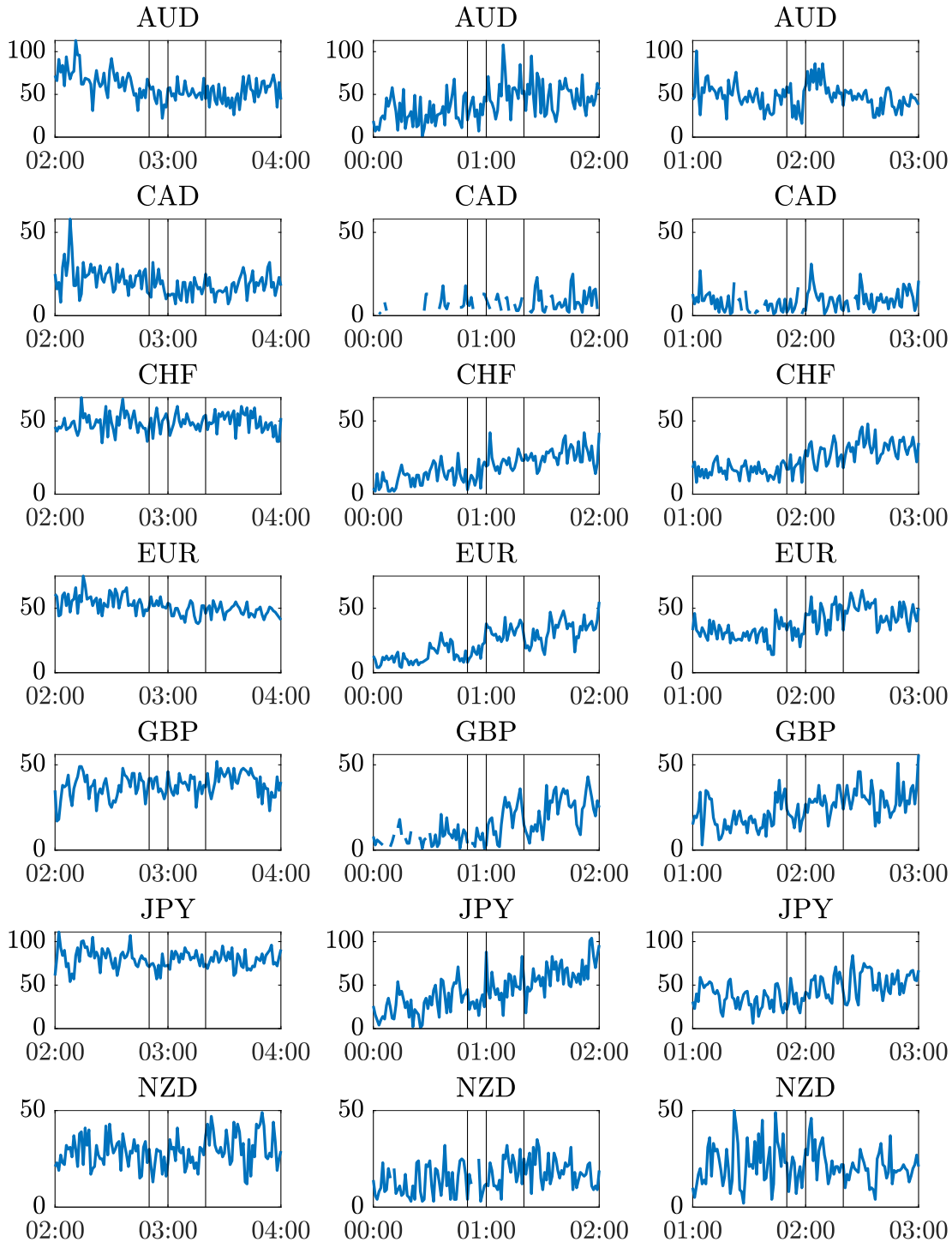


Figure 25: spot exchange rates volume on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict average number of bids and asks by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

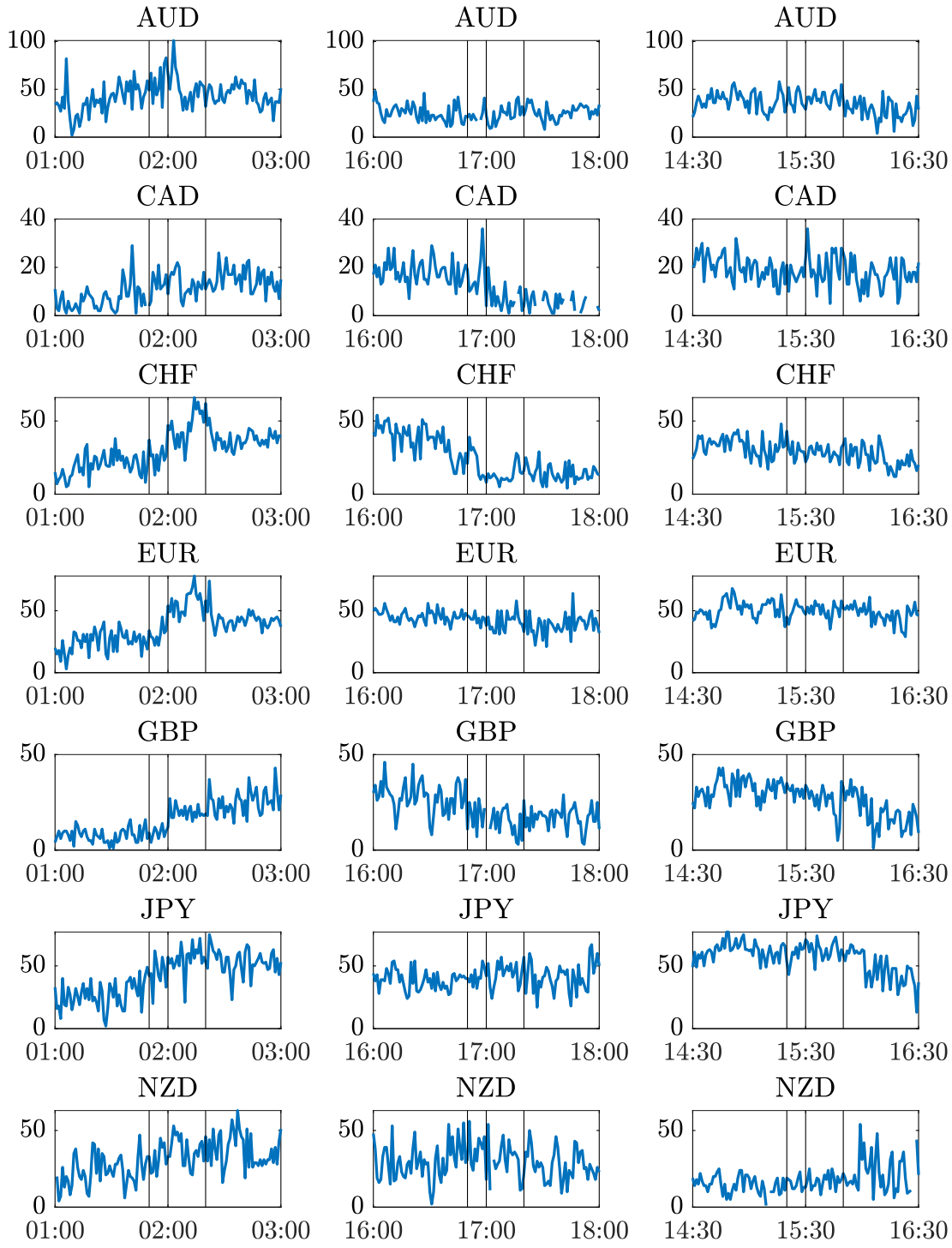


Figure 26: spot exchange rates volume on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict average number of bids and asks by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

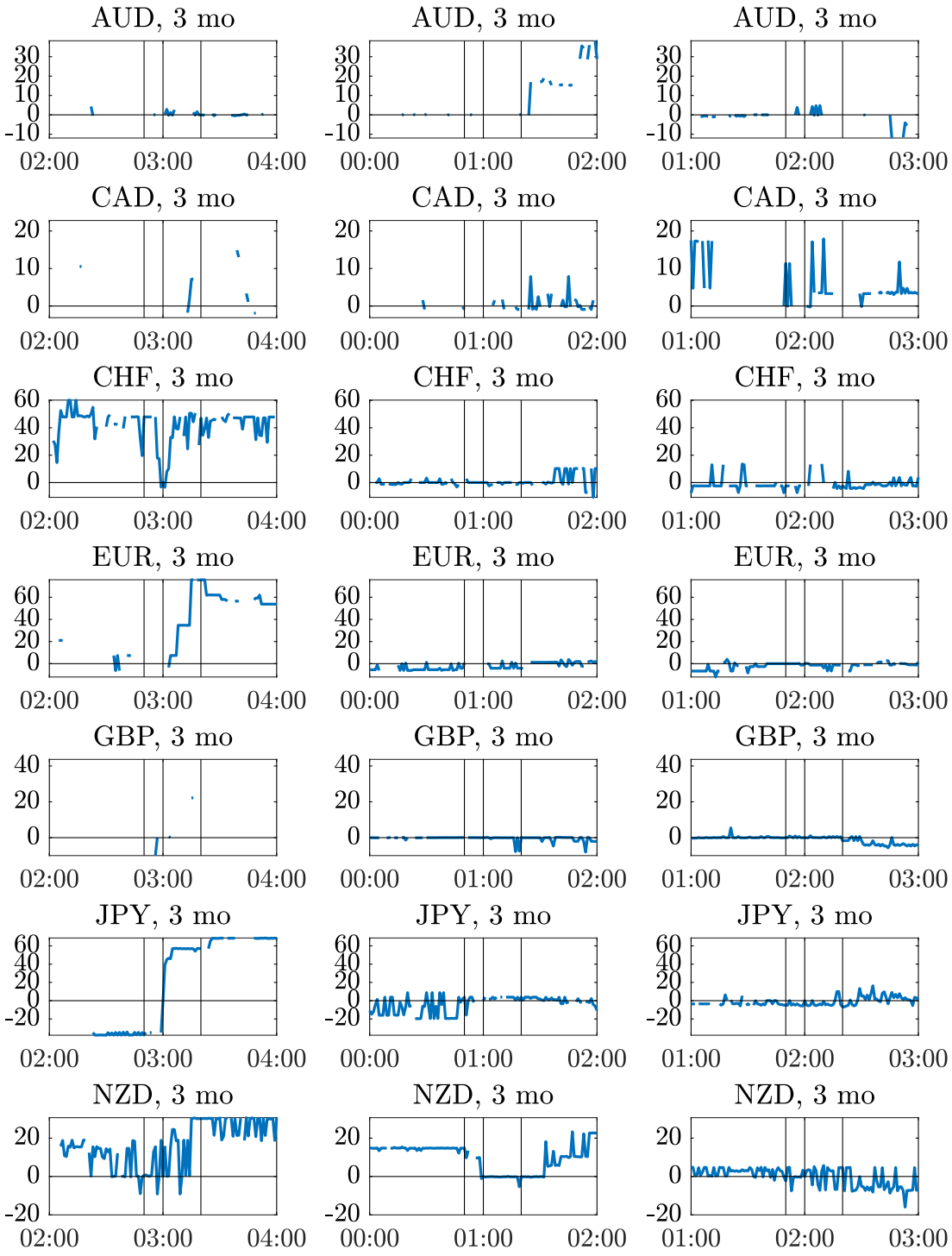


Figure 27: forward premiums on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict forward premiums at open by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

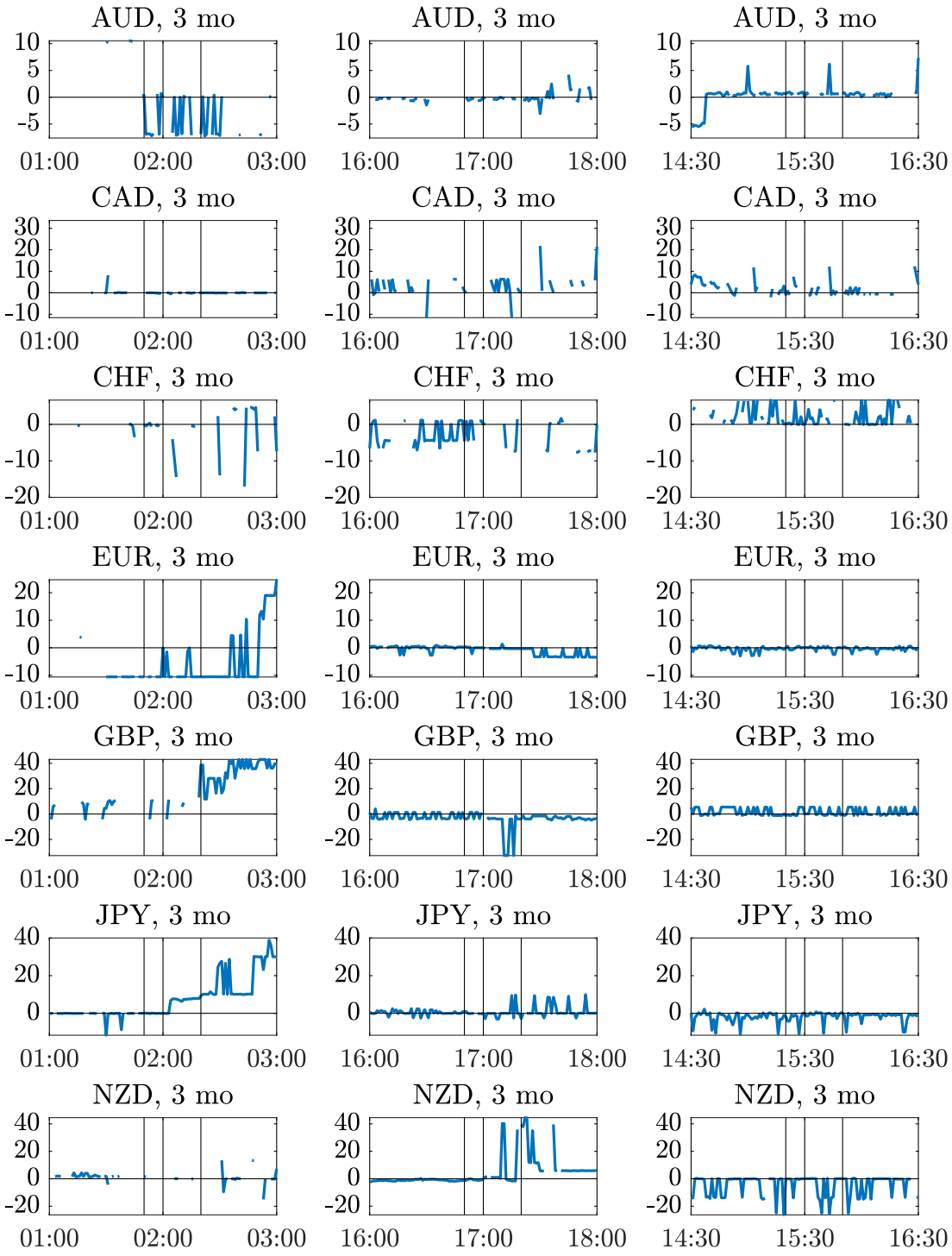


Figure 28: forward premiums on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict forward premiums at open by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

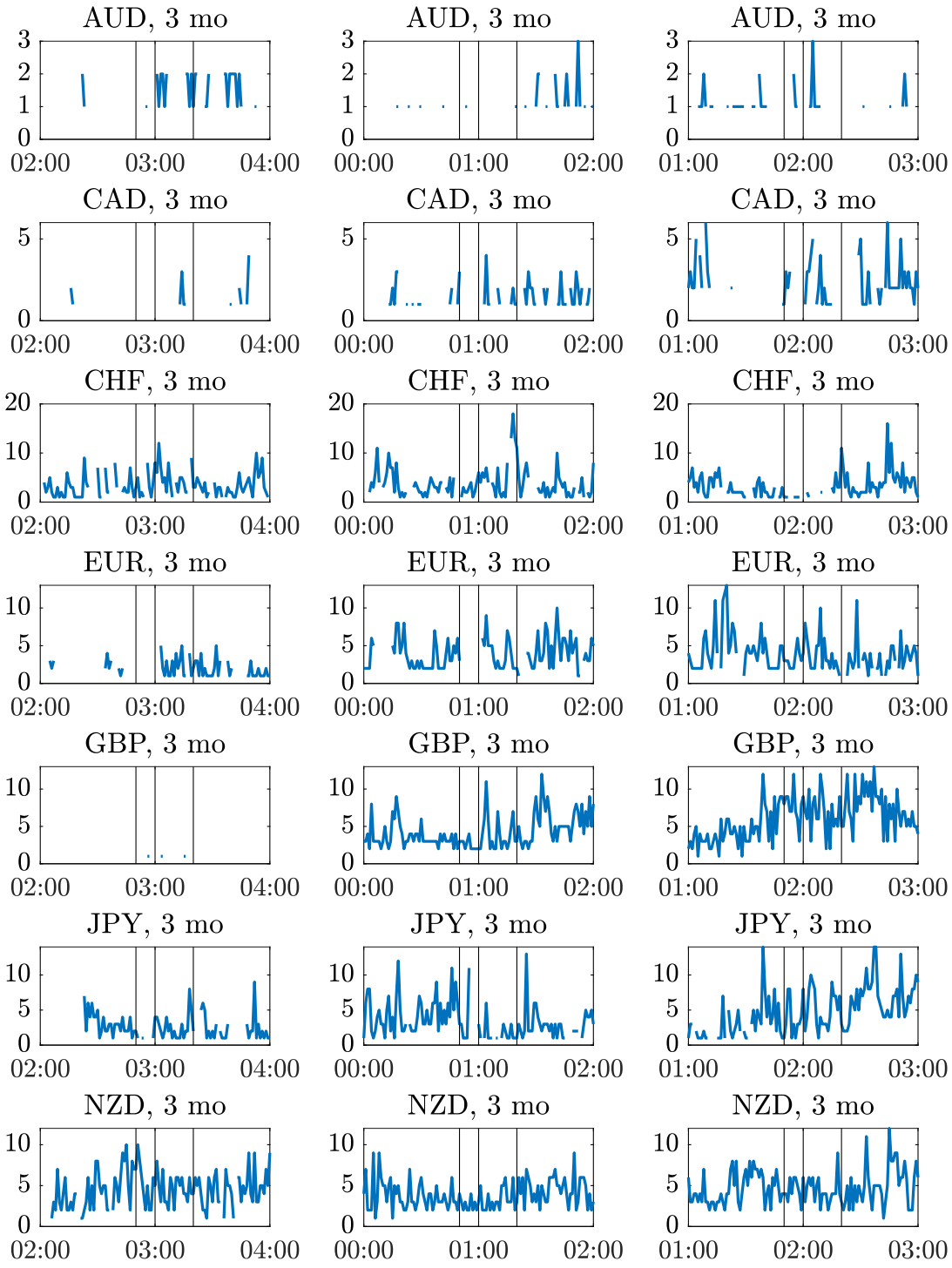


Figure 29: forward volume on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict average number of bid and ask quotes by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

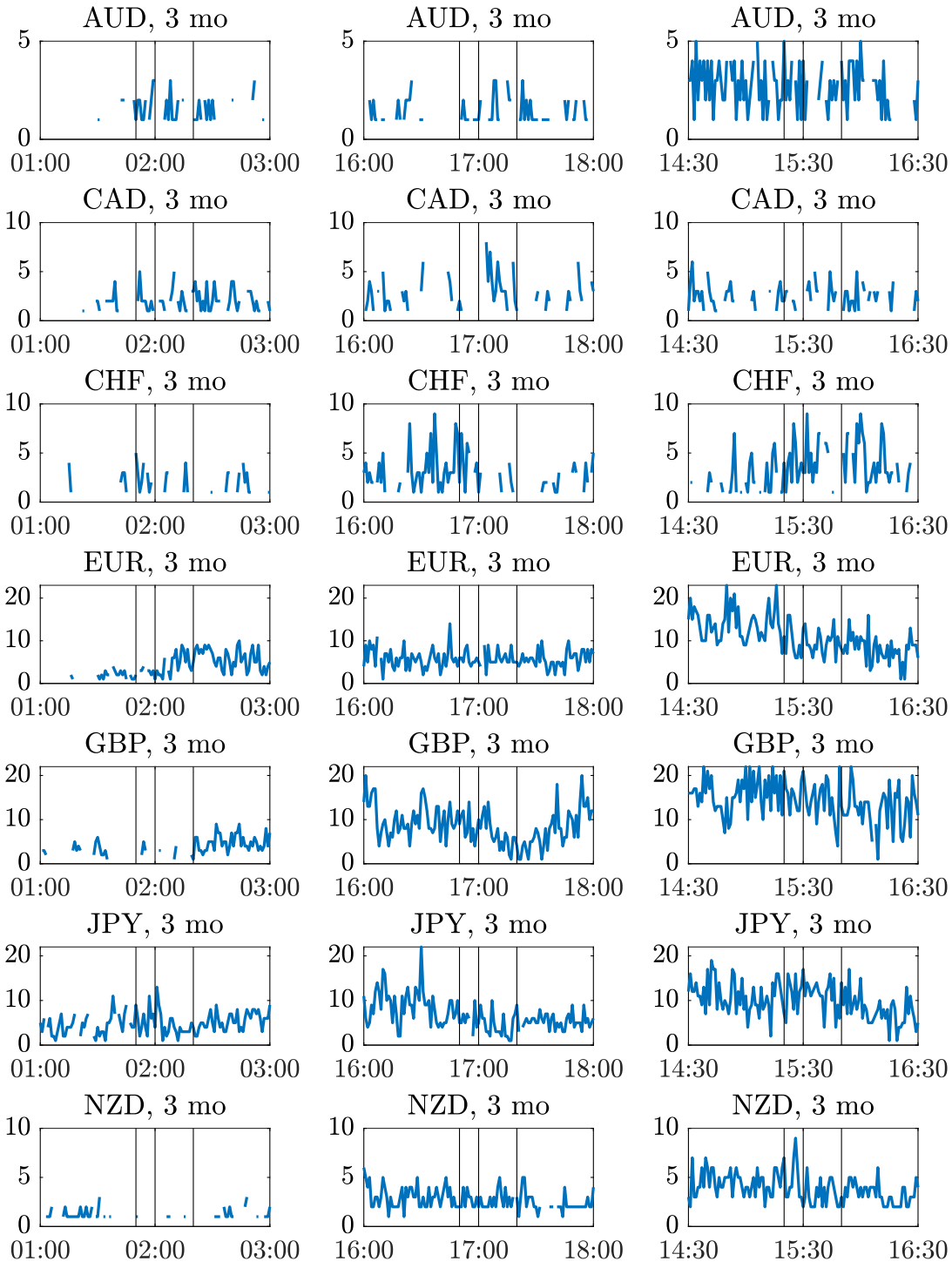


Figure 30: forward volume on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict average number of bid and ask quotes by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

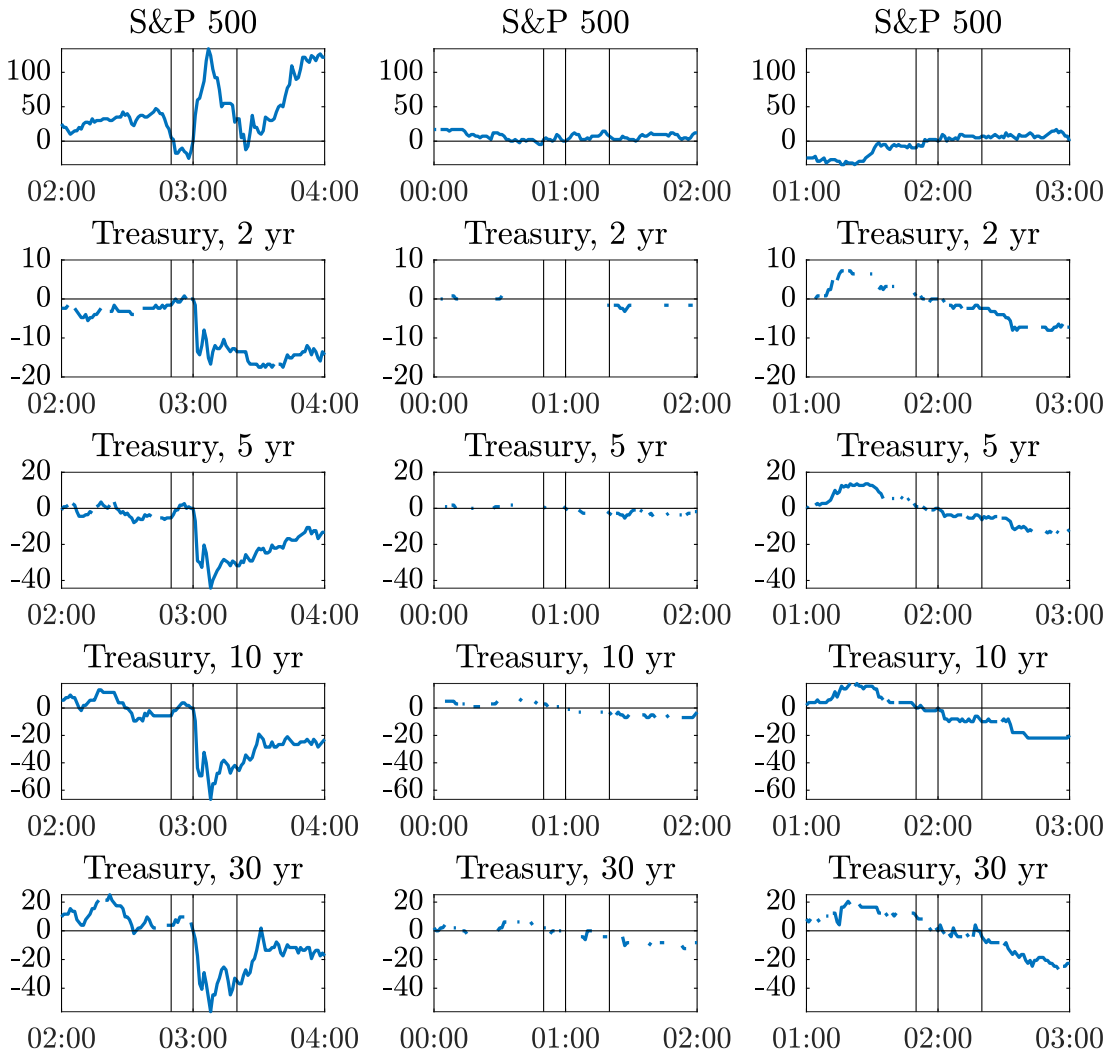


Figure 31: S&P 500 and bond futures on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict log open price (for S&P 500 future) and -1 times log open price (for bond futures) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

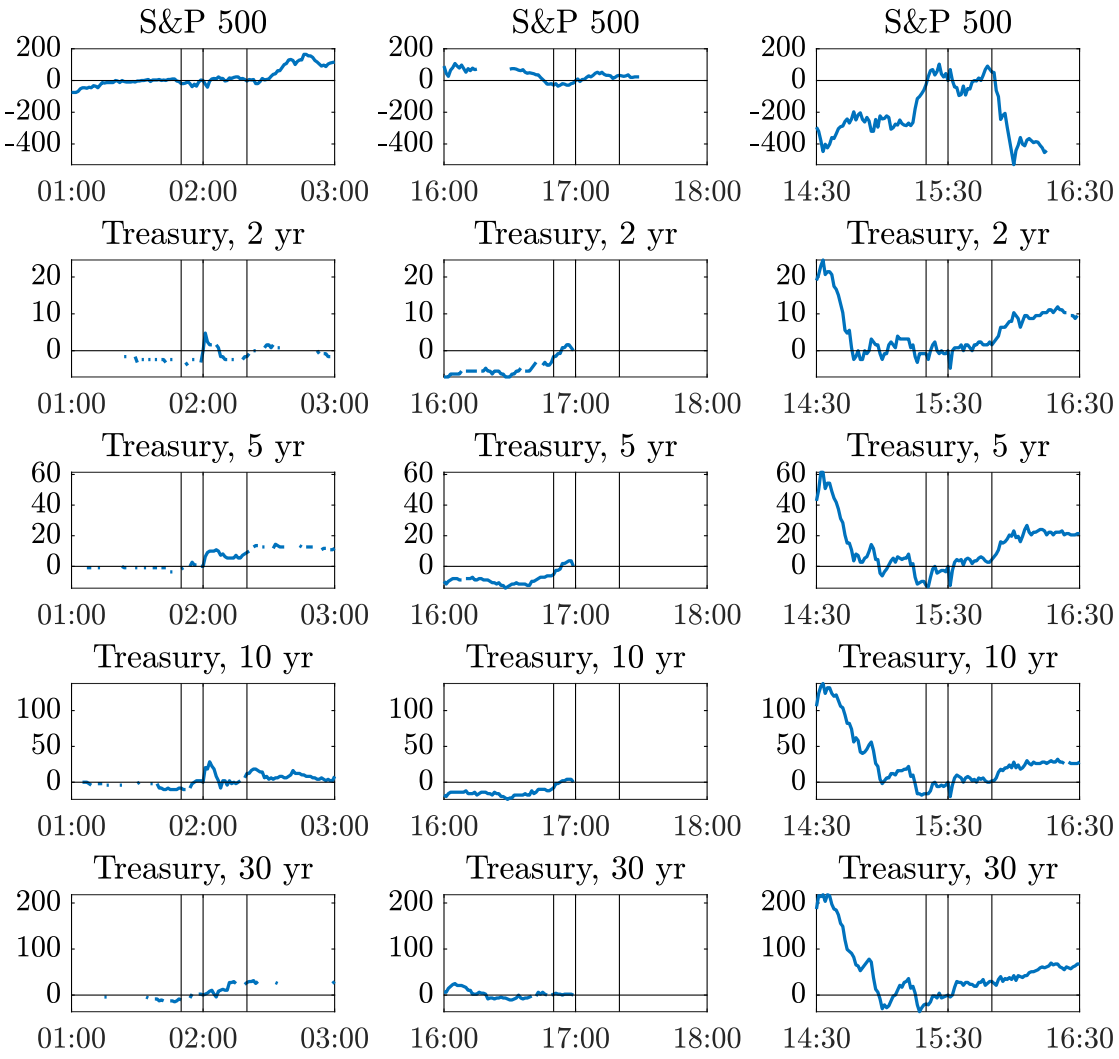


Figure 32: S&P 500 and bond futures on 10/13 (L), 10/28 (M), and 10/29 (R)

Notes: figures depict log open price (for S&P 500 future) and -1 times log open price (for bond futures) by one-minute bar, multiplied by 10000 and normalized so that each series equals zero at time of press release. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

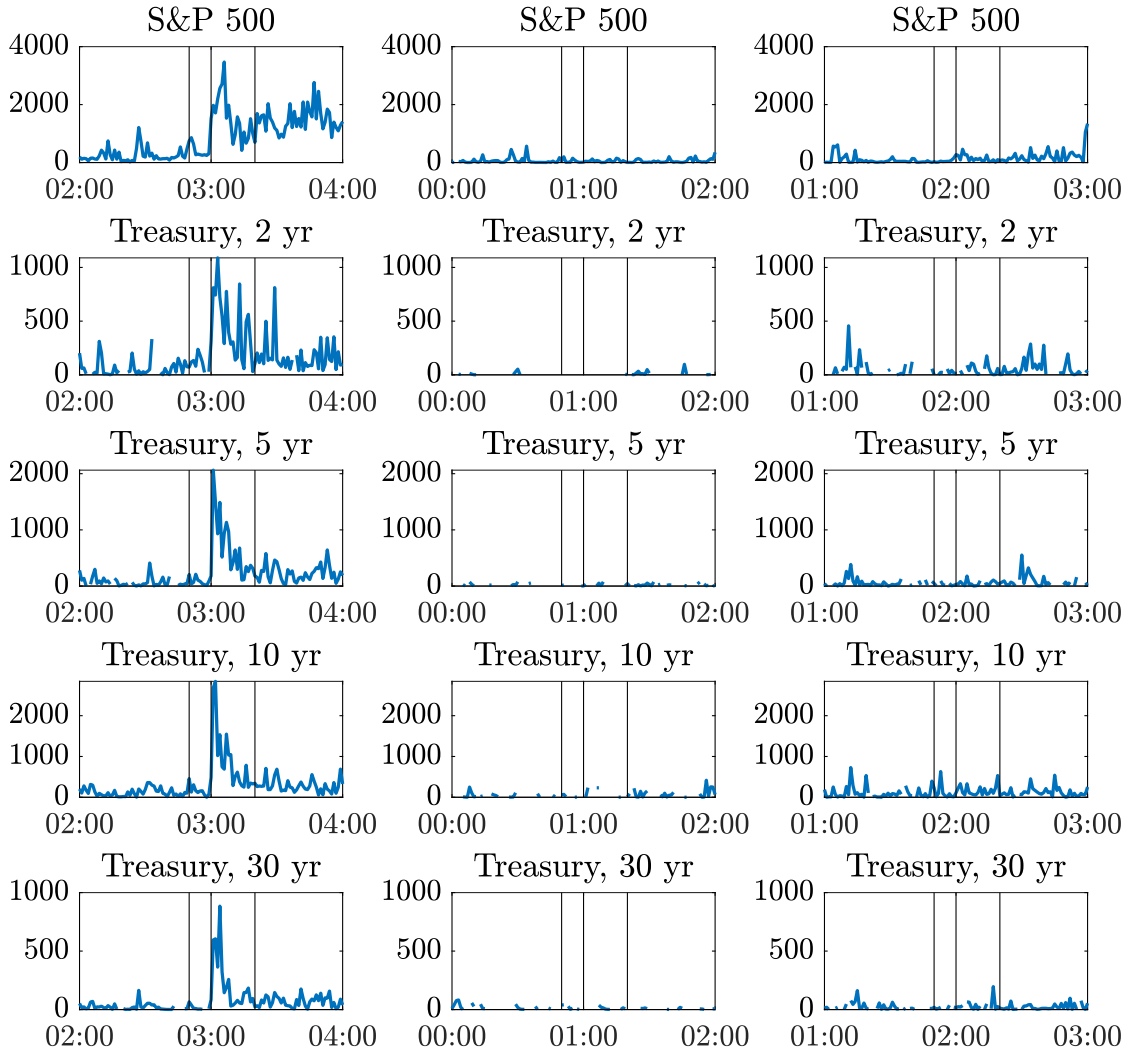


Figure 33: S&P 500 and bond futures volume on 9/18 (L), 9/24 (M), and 9/26 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

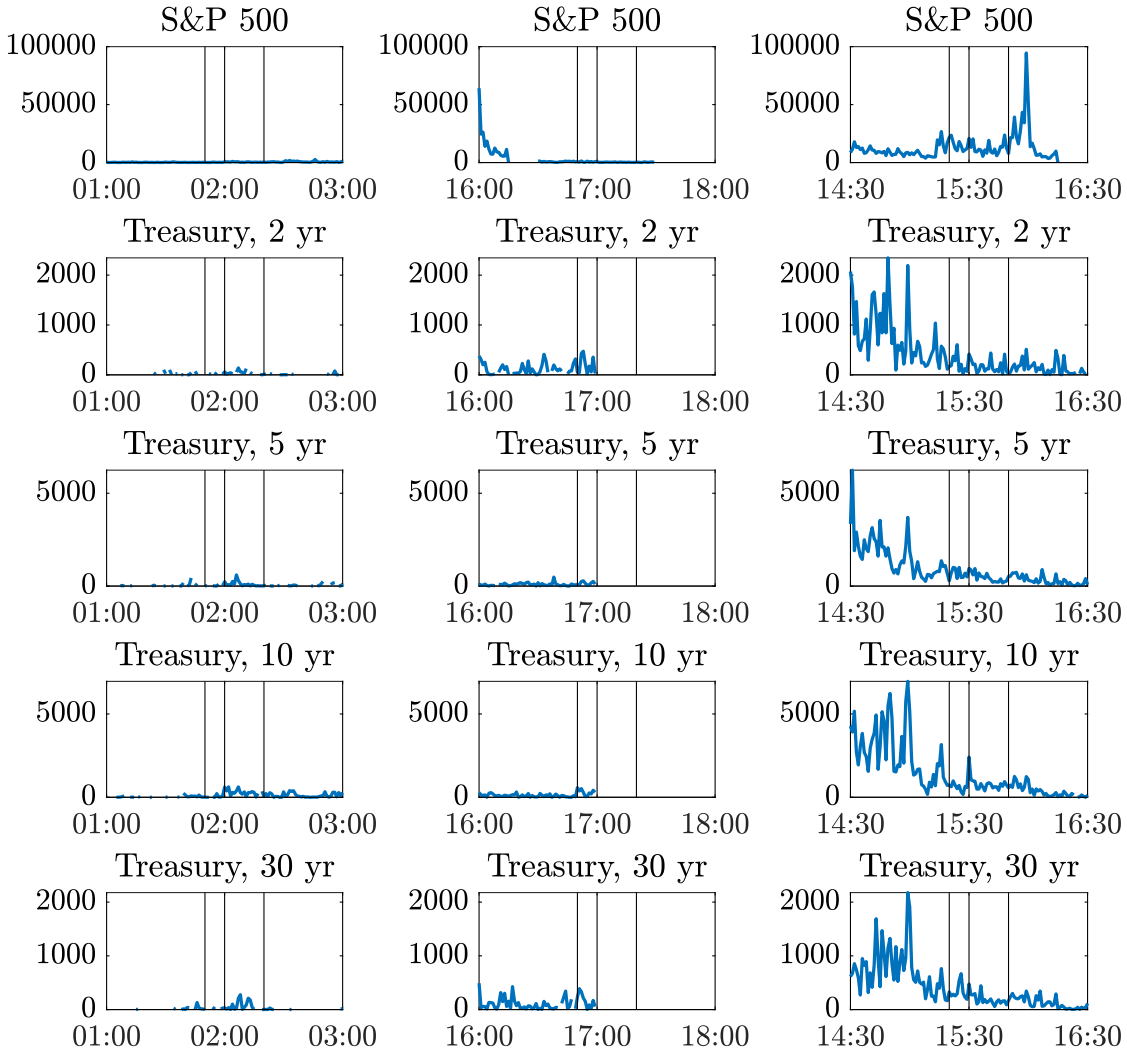


Figure 34: S&P 500 and bond futures volume on 10/13 (L), 10/28 (M), 10/29 (R)

Notes: figures depict trading volume by one-minute bar. Vertical lines depict 10 minutes prior to press release, press release, and 20 minutes after press release. All times are in EDT.

E Model equilibrium conditions

In this section we outline the full set of equilibrium conditions for the model studied in section 3. We describe the model with swap lines, as the case without swap lines is nested.

The budget constraints of the representative U.S. and Foreign agents are

$$\begin{aligned} c_t + b^s_{Ht} + b_{Ht} + q_t^{-1} b_{Ft} &= p_{Ht} y_t + (1 + r^s_{t-1}) b^s_{Ht-1} + (1 + r_{t-1}) b_{Ht-1} \\ &\quad + q_t^{-1}(1 + r^*_{t-1}) b_{Ft-1} + \left(q_t^{-1} f_{t-1} - 1\right) \eta_{t-1} - r^s_{t-1} \bar{b}^s_H + r^{sw}_{t-1} sw^*_{t-1}, \qquad (13) \\ c^*_t + q_t b^{s*}_{Ht} + q_t b^*_{Ht} + b^*_{Ft} + q_t sw^*_t &= q_t s_t^{-1} p_{Ht} y^*_t + q_t (1 + r^s_{t-1}) b^{s*}_{Ht-1} + q_t (1 + r_{t-1}) b^*_{Ht-1} \\ &\quad + (1 + r^*_{t-1}) \left(b^*_{Ft-1} + q_{t-1} sw^*_{t-1}\right) - q_t r^{sw}_{t-1} sw^*_{t-1} + (f_{t-1} - q_t) \eta^*_{t-1}, \qquad (14) \end{aligned}$$

where p_{Ht} is the price of the U.S.-endowed good relative to the U.S. aggregator and s_t is the price of the U.S.-endowed good relative to the Foreign-endowed good (the U.S.' terms of trade). Here we have already used that the balance sheet costs paid by the U.S. agent and unhedged dollar exposure costs paid by the Foreign agent are rebated by their respective governments and thus do not appear in the resource constraints. We have also used that the lump-sum taxes on the U.S. agent are used to balance the U.S. government's budget given its issuance of safe dollar debt and fees collected on swap lines. Finally, note that the distinction between b^*_{Ft} and $q_t sw^*_t$ is that the former refers to Foreign-denominated bonds held by the Foreign agent and not pledged to the U.S. agent against the swap line, whereas $q_t sw^*_t$ are Foreign-denominated bonds against which it receives sw^*_t in dollar liquidity via the swap line.

The intertemporal optimality conditions of the U.S. agent are

$$1 + \kappa_{bs} b^s_{Ht} = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}} (1 + r^s_t) + \lambda \omega_t - \frac{1}{\epsilon^d} b^s_{Ht}, \qquad (15)$$

$$1 + \kappa_{bs} b_{Ht} = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}} (1 + r_t), \qquad (16)$$

$$1 + \kappa_{bs} q_t^{-1} b_{Ft} = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}} \frac{q_t}{q_{t+1}} (1 + r^*_t), \qquad (17)$$

$$\kappa_{bs} \eta_t = \mathbb{E}_t \beta \frac{c_t}{c_{t+1}} \left[q_{t+1}^{-1} f_t - 1\right]. \qquad (18)$$

The intertemporal optimality conditions of the Foreign agent are

$$1+\kappa_{fx}uh_t^* = \mathbb{E}_t\beta\frac{c_t^*}{c_{t+1}^*}\frac{q_{t+1}}{q_t}(1+r_t^s)+\omega_t-\frac{1}{\epsilon^d}\left(b_{Ht}^{s*}+\nu_t^{sw}sw_t^*\right), \tag{19}$$

$$1+\kappa_{fx}uh_t^* \geq \mathbb{E}_t\beta\frac{c_t^*}{c_{t+1}^*}\frac{q_{t+1}}{q_t}(1+r_t), \text{ with equality if } b_{Ht}^* > \underline{b}_H^*, \tag{20}$$

$$1 = \mathbb{E}_t\beta\frac{c_t^*}{c_{t+1}^*}(1+r_t^*), \tag{21}$$

$$-\kappa_{fx}uh_t^* = \mathbb{E}_t\beta\frac{c_t^*}{c_{t+1}^*}\frac{q_{t+1}}{q_t}\left[q_{t+1}^{-1}f_t-1\right], \tag{22}$$

given unhedged dollar exposure

$$uh_t^* = b_{Ht,s}^* + b_{Ht}^* - \eta_t^*. \tag{23}$$

The intratemporal optimality conditions of each agent are

$$c_{Ht} = \left(\frac{1}{2}+\varsigma\right)(p_{Ht})^{-\sigma}c_t, \tag{24}$$

$$c_{Ft} = \left(\frac{1}{2}-\varsigma\right)(s_t^{-1}p_{Ht})^{-\sigma}c_t, \tag{25}$$

$$c_{Ht}^* = \left(\frac{1}{2}-\varsigma\right)(q_t p_{Ht})^{-\sigma}c_t^*, \tag{26}$$

$$c_{Ft}^* = \left(\frac{1}{2}+\varsigma\right)(q_t s_t^{-1}p_{Ht})^{-\sigma}c_t^*, \tag{27}$$

given relative prices implied by standard CES price indices

$$p_{Ht} = \left[\left(\frac{1}{2}+\varsigma\right)+\left(\frac{1}{2}-\varsigma\right)s_t^{\sigma-1}\right]^{\frac{1}{\sigma-1}}, \tag{28}$$

$$q_t = s_t\left(\frac{\left(\frac{1}{2}+\varsigma\right)+\left(\frac{1}{2}-\varsigma\right)s_t^{\sigma-1}}{\left(\frac{1}{2}-\varsigma\right)s_t^{1-\sigma}+\left(\frac{1}{2}+\varsigma\right)}\right)^{\frac{1}{1-\sigma}}. \tag{29}$$

Finally, market clearing requires

$$b_{Ht}^s + b_{Ht}^{s*} = \bar{b}_{Ht}^s, \tag{30}$$

$$b_{Ht} + b_{Ht}^* = 0, \tag{31}$$

$$b_{Ft} + b_{Ft}^* + q_t sw_t^* = 0, \tag{32}$$

$$\eta_t + \eta_t^* = 0, \tag{33}$$

$$c_{Ht} + c_{Ht}^* = y_t. \tag{34}$$

By Walras' Law, the Foreign-endowed goods market also clears.

In the absence of swap lines, $sw_t^* = 0$ and (13)-(34) constitute 22 equations in 22 unknowns

$$\{c_t, c_{Ht}, c_{Ft}, b_{Ht}^s, b_{Ht}, b_{Ft}, \eta_t, c_t^*, c_{Ht}^*, c_{Ft}^*, b_{Ht}^{s*}, b_{Ht}^*, b_{Ft}^*, \eta_t^*, uh_t^*, p_{Ht}, s_t, q_t, f_t, r_t^*, r_t, r_t^s\}.$$

With swap lines, sw_t^* is an additional unknown described by

$$\nu_t^{sw}\left(\omega_t - \frac{1}{\epsilon^d}\left(b_{Ht}^{s*} + \nu_t^{sw} sw_t^*\right)\right) \leq \mathbb{E}_t \beta \frac{c_t^*}{c_{t+1}^*}\frac{q_{t+1}}{q_t} r_t^{sw}, \tag{35}$$

with equality if $sw_t^* > 0$.

F Proofs of analytical results

In this section we prove Propositions 1 and 2 from the main text.

F.1 Proposition 1

Proof. Combining (6) and (7) at the deterministic steady-state yields

$$1 - \lambda\omega + \frac{1}{\epsilon^d} b_H^s + \kappa_{bs} b_H^s = 1 - \omega + \frac{1}{\epsilon^d} b_H^{s*} + \kappa_{fx} uh^*.$$

Re-arranging yields

$$\frac{1}{\epsilon^d} b_H^{s*} + \kappa_{fx} uh^* - \frac{1}{\epsilon^d} b_H^s - \kappa_{bs} b_H^s = (1-\lambda)\omega.$$

The left-hand side is increasing in b_H^{s*} and falling in b_H^s: it captures the relative holdings of safe dollar assets in Foreign versus the U.S.. The right-hand side is the relative non-pecuniary value of these assets in Foreign versus the U.S.. Using the definition of uh^* and market clearing in safe dollar bonds implies that

$$b_H^{s*} = \frac{1}{\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}}(1-\lambda)\omega + \frac{\kappa_{bs} + \frac{1}{\epsilon^d}}{\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}}\bar{b}_H^s - \frac{\kappa_{fx}}{\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}}\left[b_H^* - \eta^*\right],$$

and thus

$$uh^* = \frac{1}{\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}}(1-\lambda)\omega + \frac{\kappa_{bs} + \frac{1}{\epsilon^d}}{\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}}\bar{b}_H^s + \frac{\kappa_{bs} + 2\frac{1}{\epsilon^d}}{\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}}\left[b_H^* - \eta^*\right].$$

(10) and (11) at the deterministic steady-state imply that

$$-\kappa_{bs}\eta = \kappa_{fx} uh^*.$$

Substituting in the above result and using market clearing in forwards, we obtain

$$\begin{aligned}\eta^* = &\frac{\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}(1-\lambda)\omega \\ &+ \frac{\kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}\bar{b}_H^s \\ &+ \frac{\kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}b_H^*,\end{aligned}$$

and thus

$$\begin{aligned}uh^* = &\frac{\kappa_{bs}}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}(1-\lambda)\omega \\ &+ \frac{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}\bar{b}_H^s \\ &+ \frac{\kappa_{bs}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}b_H^*,\end{aligned}$$

and

$$\begin{aligned}b_H^{s*} = &\frac{\kappa_{bs} + \kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}(1-\lambda)\omega \\ &+ \frac{\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)(\kappa_{bs} + \kappa_{fx})}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}\bar{b}_H^s \\ &- \frac{\kappa_{bs}\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs} + \kappa_{fx} + 2\frac{1}{\epsilon^d}\right) + \kappa_{fx}\left(\kappa_{bs} + 2\frac{1}{\epsilon^d}\right)}b_H^*.\end{aligned}$$

Now note that given the above expression for uh^* and market clearing in dollar

bonds,

$$\begin{aligned}\kappa_{fx} uh^* - \kappa_{bs} b_H,& \\ &= \kappa_{fx} uh^* + \kappa_{bs} b_H^*, \\ &> 0\end{aligned}$$

for b_H^* not too negative and λ sufficiently close to one. It follows from (8) and (9) at the deterministic steady-state that

$$1 + \kappa_{fx} uh^* > \beta(1+r) = 1 + \kappa_{bs} b_H,$$

and thus the borrowing constraint in dollar bonds must bind, for $\underline{b}_H^*$ sufficiently tight.

Finally, for b_H^* not too negative and λ sufficiently close to one, it is also clear that $\eta^* > 0$, $uh^* > 0$, and $b_H^{s*} \in [0, \bar{b}_H^s]$ as claimed. That is, Foreign owns some (but not all) safe dollar bonds, partially hedging these by selling dollars forward and retaining some unhedged exposure.

This in turn implies a CIP deviation. In particular,

$$\beta = \frac{1 - \kappa_{bs} \underline{b}_H^*}{1+r} = \frac{1}{1+r^*},$$

where the latter follows from the optimality conditions for Foreign-denominated bonds

$$\begin{aligned}1 + \kappa_{bs} q^{-1} b_F &= \beta(1+r^*), \\ 1 &= \beta(1+r^*),\end{aligned}$$

which also imply $b_F = 0$ in steady-state. Hence, (10) implies

$$\kappa_{bs} \eta = \frac{f}{q} \frac{1}{1+r^*} - \frac{1 - \kappa_{bs} \underline{b}_H^*}{1+r}$$

and thus

$$(1+r) - \frac{q}{f}(1+r^*) = \frac{q}{f} \kappa_{bs} \eta (1+r)(1+r^*) - \frac{q}{f} \kappa_{bs} \underline{b}_H^* (1+r^*),$$

which is negative for $\underline{b}_H^*$ sufficiently tight, given $\eta = -\eta^* < 0$ as derived above. Intuitively, there are two sources of deviations from CIP in steady-state: Foreign

borrowing demand in dollars raises this interest rate, while Foreign sales of dollars forward raises the forward premium. Provided the dollar borrowing constraint is sufficiently tight, the latter effect dominates and the CIP deviation is negative.

We can finally characterize the return on safe dollar bonds r^s. Using (7),

$$\beta\left(1+r^s\right)-1=-\omega+\frac{1}{\epsilon^d}b_H^{s*}+\kappa_{fx}uh^*.$$

Using the above expressions for b_H^{s*} and uh^*, it follows that the above expression is negative for ω sufficiently large and λ sufficiently close to one. Thus,

$$\beta\left(1+r^s\right)-1<0\leq-\kappa_{bs}\underline{b}_H^*=\beta(1+r)-1,$$

so $r^s<r$ as claimed. □

F.2 Proposition 2

Proof. We first characterize the steady-state with swap lines, paralleling the proof of Proposition 1, before we take comparative statics.

Combining (6), (7), and (12) evaluated at the deterministic steady-state, the first two generalized to account for swap lines, yields

$$1-\lambda\omega+\frac{1}{\epsilon^d}b_{H,s}+\kappa_{bs}b_{H,s}=\beta(1+r^s)=1+\kappa_{fx}uh^*-\frac{1}{\nu^{sw}}\beta r^{sw}.$$

Using market clearing in safe dollar bonds, it follows that

$$b_H^{s*}=\bar{b}_H^s+\frac{1}{\kappa_{bs}+\frac{1}{\epsilon^d}}\left(-\kappa_{fx}uh^*+\frac{1}{\nu^{sw}}\beta r^{sw}-\lambda\omega\right), \tag{36}$$

and using as well the definition of uh^* it follows that

$$b_H^{s*}=\frac{1}{\kappa_{fx}+\kappa_{bs}+\frac{1}{\epsilon^d}}\left[-\lambda\omega+\frac{1}{\nu^{sw}}\beta r^{sw}\right]+\frac{\kappa_{bs}+\frac{1}{\epsilon^d}}{\kappa_{fx}+\kappa_{bs}+\frac{1}{\epsilon^d}}\bar{b}_H^s-\frac{\kappa_{fx}}{\kappa_{fx}+\kappa_{bs}+\frac{1}{\epsilon^d}}\left[b_H^*-\eta^*\right],$$

and thus

$$uh^*=\frac{1}{\kappa_{fx}+\kappa_{bs}+\frac{1}{\epsilon^d}}\left[-\lambda\omega+\frac{1}{\nu^{sw}}\beta r^{sw}\right]+\frac{\kappa_{bs}+\frac{1}{\epsilon^d}}{\kappa_{fx}+\kappa_{bs}+\frac{1}{\epsilon^d}}\left[\bar{b}_H^s+b_H^*-\eta^*\right].$$

Let us now focus for expositional simplicity on the case with $\underline{b}_H^* = 0$, in which case the same arguments as in the proof of Proposition 1 imply the dollar borrowing constraint is binding and $b_H^* = \underline{b}_H^* = 0$ and thus $b_H = 0$ as well. By continuity the arguments which follow also hold for $\underline{b}_H^* < 0$ but sufficiently tight.

Again using (10) and (11) at the deterministic steady-state, the above result, and market clearing in forwards, we obtain

$$\eta^* = \frac{\kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)}{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d} + \kappa_{fx}\right) + \kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)} \bar{b}_H^s + \frac{\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d} + \kappa_{fx}\right) + \kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)} \left[-\lambda\omega + \frac{1}{\nu^{sw}}\beta r^{sw}\right],$$

and thus

$$uh^* = \frac{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)}{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d} + \kappa_{fx}\right) + \kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)} \bar{b}_H^s + \frac{\kappa_{bs}}{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d} + \kappa_{fx}\right) + \kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)} \left[-\lambda\omega + \frac{1}{\nu^{sw}}\beta r^{sw}\right].$$

and

$$b_{H,s}^* = \frac{\kappa_{bs} + \kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d} + \kappa_{fx}\right) + \kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)} \left[-\lambda\omega + \frac{1}{\nu^{sw}}\beta r^{sw}\right] + \frac{\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)\left(\kappa_{bs} + \kappa_{fx}\right)}{\kappa_{bs}\left(\kappa_{bs} + \frac{1}{\epsilon^d} + \kappa_{fx}\right) + \kappa_{fx}\left(\kappa_{bs} + \frac{1}{\epsilon^d}\right)} \bar{b}_H^s.$$

The take-up of swap lines is defined by (6) and (7) generalized to account for swap lines

$$1 - \omega + \frac{1}{\epsilon^d}\left(b_H^{s*} + \nu^{sw} sw^*\right) + \kappa_{fx} uh^* = \beta(1 + r^s) = 1 - \lambda\omega + \frac{1}{\epsilon^d} b_H^s + \kappa_{bs} b_H^s,$$

which implies using safe dollar bond market clearing and (36) that

$$sw^* = \frac{\epsilon^d}{\nu^{sw}}\left[(1-\lambda)\omega - \frac{1}{\epsilon^d}\bar{b}_H^s + \frac{\frac{1}{\epsilon^d}}{\kappa_{bs} + \frac{1}{\epsilon^d}}\kappa_{fx} uh^* - \frac{\kappa_{bs} + 2\frac{1}{\epsilon^d}}{\kappa_{bs} + \frac{1}{\epsilon^d}}\left(\frac{1}{\nu^{sw}}\beta r^{sw} - \lambda\omega\right)\right].$$

The CIP deviation is again

$$1 + r - \frac{q}{f}(1 + r^*) = \frac{q}{f}\kappa_{bs}\eta(1 + r)(1 + r^*) < 0,$$

and the interest rate r^s is now

$$\begin{aligned} r^s &= 1 + r^s - 1, \\ &= \frac{1}{\beta}\left(1 - \lambda\omega + \frac{1}{\epsilon^d}b_H^s + \kappa_{bs}b_H^s\right) - 1, \\ &= \frac{1}{\beta}\left(1 + \kappa_{fx}uh^* - \frac{1}{\nu^{sw}}\beta r^{sw}\right) - 1. \end{aligned}$$

Now by inspection of these results:

- $\frac{db_H^{s*}}{d[r^{sw}/\nu^{sw}]} = \frac{\kappa_{bs}+\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)}\beta > 0.$
- $\frac{duh^*}{d[r^{sw}/\nu^{sw}]} = \frac{\kappa_{bs}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)}\beta > 0.$
- $\frac{d\eta^*}{d[r^{sw}/\nu^{sw}]} = \frac{\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)}\beta > 0.$
- $\frac{dr^s}{d[r^{sw}/\nu^{sw}]} = \frac{\kappa_{bs}\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)} - 1 < 0.$

It follows that given a decline in r^{sw} or increase in ν^{sw}, Foreign ownership of safe dollar bonds falls, Foreign's unhedged dollar exposure and hedging costs fall, the CIP deviation thus compresses (because the forward premium rises), and the safe interest rate rises (implying the liquidity premium falls).

It remains to characterize the response of the real exchange rate q. By goods market clearing, the response of q is inversely related to the steady-state net interest income earned by Foreign (in dollars)

$$r^s b_H^{s*} + (q^{-1}f - 1)\eta^* - r^{sw}sw^*.$$

When this rises, steady-state Foreign consumption rises relative to U.S. consumption, depreciating the dollar in light of consumption home bias.

Using the above results,

$r^s b_H^{s*} + (q^{-1}f - 1)\eta^* - r^{sw}sw^*$

$$
\begin{aligned}
&= \left[\frac{1}{\beta}\left(1+\kappa_{fx}uh^* - \frac{1}{\nu^{sw}}\beta r^{sw}\right) - 1\right]\left[\bar{b}_H^s + \frac{1}{\kappa_{bs}+\frac{1}{\epsilon^d}}\left(-\kappa_{fx}uh^* + \frac{1}{\nu^{sw}}\beta r^{sw} - \lambda\omega\right)\right] \\
&\quad - \frac{1}{\beta}\frac{\kappa_{fx}^2}{\kappa_{bs}}\left(uh^*\right)^2 \\
&\quad - r^{sw}\left[\frac{\epsilon^d}{\nu}\left[(1-\lambda)\omega - \frac{1}{\epsilon^d}\bar{b}_H^s + \frac{\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\kappa_{fx}uh^* - \frac{\kappa_{bs}+2\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\left(\frac{1}{\nu^{sw}}\beta r^{sw} - \lambda\omega\right)\right]\right].
\end{aligned}
$$

We then have that:

$$
\begin{aligned}
&\frac{d\left[r^s b_H^{s*} + (q^{-1}f-1)\eta^* - r^{sw}sw^*\right]}{d[r^{sw}/\nu^{sw}]} = \\
&\qquad - b_H^{s*} + r^s\frac{\beta}{\kappa_{bs}+\frac{1}{\epsilon^d}} - \nu^{sw}sw^* + r^{sw}\frac{\epsilon^d}{\nu^{sw}}\frac{\kappa_{bs}+2\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\beta \\
&\quad + \left[\frac{1}{\beta}\kappa_{fx}b_H^{s*} - r^s\frac{\kappa_{fx}}{\kappa_{bs}+\frac{1}{\epsilon^d}} - \frac{2}{\beta}\frac{\kappa_{fx}^2}{\kappa_{bs}}uh^* - r^{sw}\frac{\epsilon^d}{\nu^{sw}}\frac{\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\kappa_{fx}\right]\frac{duh^*}{d[r^{sw}/\nu^{sw}]}.
\end{aligned}
$$

Some of these terms can naturally be combined. In particular,

$$
\begin{aligned}
&-b_H^{s*} + \frac{\kappa_{fx}}{\beta}b_H^{s*}\frac{duh^*}{d[r^{sw}/\nu^{sw}]} \\
&\qquad = -b_H^{s*}\left[1 - \frac{\kappa_{bs}\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)}\right], \\
&\qquad < 0, \\
&r^s\frac{\beta}{\kappa_{bs}+\frac{1}{\epsilon^d}} - r^s\frac{\kappa_{fx}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\frac{duh^*}{d[r^{sw}/\nu^{sw}]} \\
&\qquad = r^s\frac{\beta}{\kappa_{bs}+\frac{1}{\epsilon^d}}\left[1 - \frac{\kappa_{bs}\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)}\right], \\
&\qquad > 0, \\
&r^{sw}\frac{\epsilon^d}{\nu}\frac{\kappa_{bs}+2\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\beta - r^{sw}\frac{\epsilon^d}{\nu^{sw}}\frac{\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\kappa_{fx}\frac{duh^*}{d[r^{sw}/\nu^{sw}]} \\
&\qquad = r^{sw}\frac{\epsilon^d}{\nu^{sw}}\frac{\kappa_{bs}+2\frac{1}{\epsilon^d}}{\kappa_{bs}+\frac{1}{\epsilon^d}}\beta\times \\
&\qquad\quad \left[1 - \frac{\frac{1}{\epsilon^d}}{\kappa_{bs}+2\frac{1}{\epsilon^d}}\frac{\kappa_{bs}\kappa_{fx}}{\kappa_{bs}\left(\kappa_{bs}+\frac{1}{\epsilon^d}+\kappa_{fx}\right)+\kappa_{fx}\left(\kappa_{bs}+\frac{1}{\epsilon^d}\right)}\right], \\
&\qquad > 0.
\end{aligned}
$$

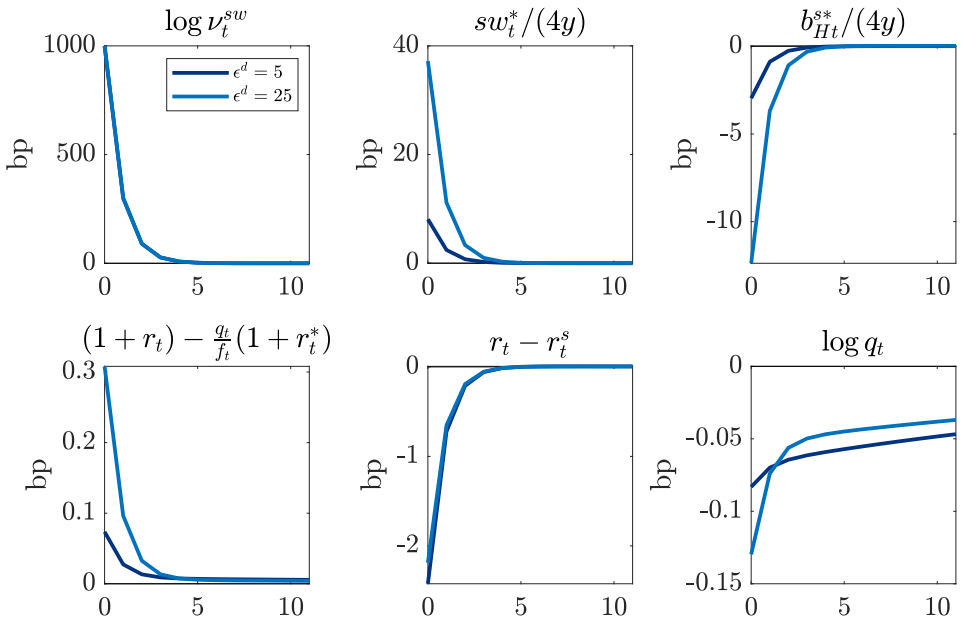


Figure 35: effects of shock to $\log \nu_t^{sw}$

Notes: $\log \nu_t^{sw}$ assumed to follow AR(1) process with persistence 0.3.

When r^s and r^{sw} are sufficiently small, it follows that Foreign's relative wealth rises when r^{sw}/ν^{sw} falls. r^s and r^{sw} being sufficiently small ensures that the wealth transfer away from Foreign due to its decline in Foreign saving in safe dollar bonds and increase in swap line usage does not outweigh the wealth transfer to Foreign due to its higher interest income on safe dollar bonds, lower hedging costs paid to Foreign, and lower cost of accessing the swap line. □

G Simulation of other shocks

Finally, in this section we present the simulated effects of other shocks in the model studied in section 3.

Figure 35 depicts the impulse responses to an increase in $\log \nu_t^{sw}$ by 0.1, assuming the latter follows an AR(1) with persistence 0.3. The effects are qualitatively the same as a decline in the cost of accessing swap lines in Figure 6.

Figure 36 depicts the impulse responses to a $\log \bar{b}_{Ht}^s$ innovation of 0.1, assuming this follows an AR(1) with persistence 0.3 for comparability with the swap line experiments. As described in the main text, the increase in safe dollar bond supply reduces

the liquidity premium like swap lines, but has contrasting effects on Foreign hedging demand (now depicted in the top middle panel) and hence the CIP deviation.

Figure 37 depicts the impulse responses to an $\log \omega_t$ innovation of 0.1, assuming this follows an AR(1) process with persistence 0.3 as well. We contrast the response in the case without swap lines (or swap lines which are locally not used), to the case with swap line usage. Absent swap lines, the increase in the demand for safe dollar assets raises the liquidity premium, widens the CIP deviation, and appreciates the dollar. With swap lines, swap line usage rises and both the widening of the CIP deviation and appreciation of the dollar is eliminated.

Finally, Figures 38 and 39 depict the impulse responses to $\log \kappa_{fx,t}$ and $\log \kappa_{bs,t}$ innovations of size 0.1, assuming each follows an AR(1) process with persistence 0.3 and assuming for simplicity no swap lines. As these imply an increase in the Foreign demand for hedging and decrease in the U.S. willingness to provide hedging services, respectively, they both imply a widening of the CIP deviation. Where these shocks are distinguished is by their implications for the quantity of forward contracts traded, shown in the top middle panel, as well as the dollar. An increase in Foreign hedging demand causes an increase in hedging activity, while a decrease in the U.S. willingness to provide hedging services causes a decline in hedging activity. The former is associated with a rise in relative U.S. wealth and thus dollar appreciation, while the latter a reduction in relative U.S. wealth and thus dollar depreciation.

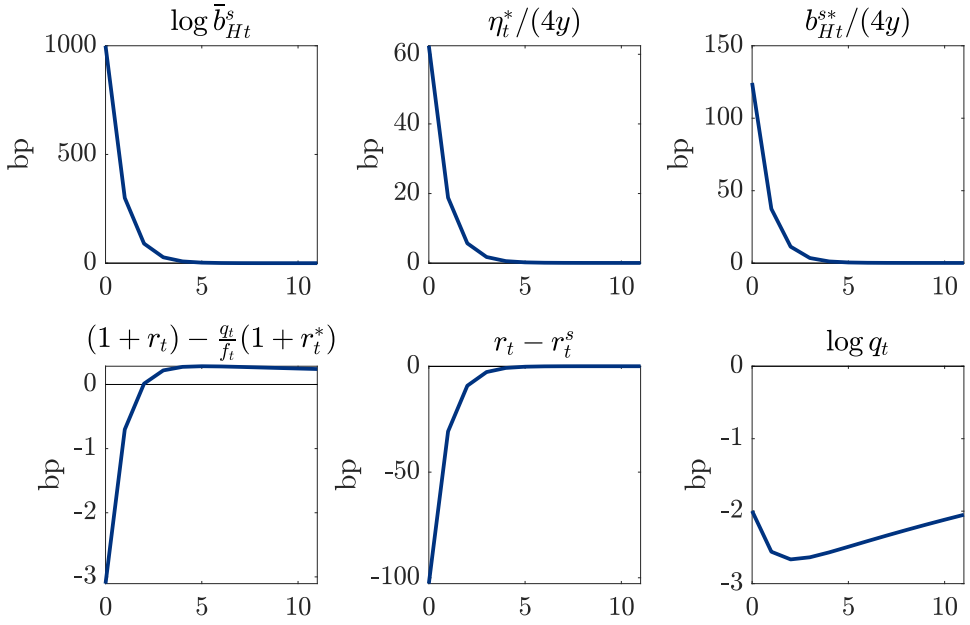


Figure 36: effects of shock to $\log \bar{b}^s_{Ht}$

Notes: $\log \bar{b}^s_{Ht}$ assumed to follow AR(1) process with persistence 0.3.

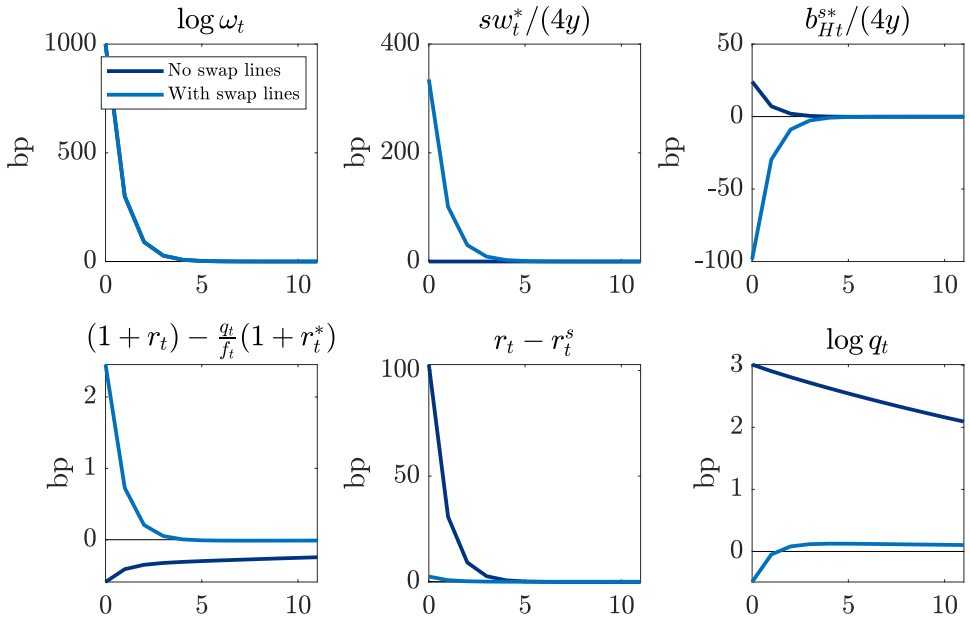


Figure 37: effects of shock to $\log \omega_t$

Notes: $\log \omega_t$ assumed to follow AR(1) process with persistence 0.3.

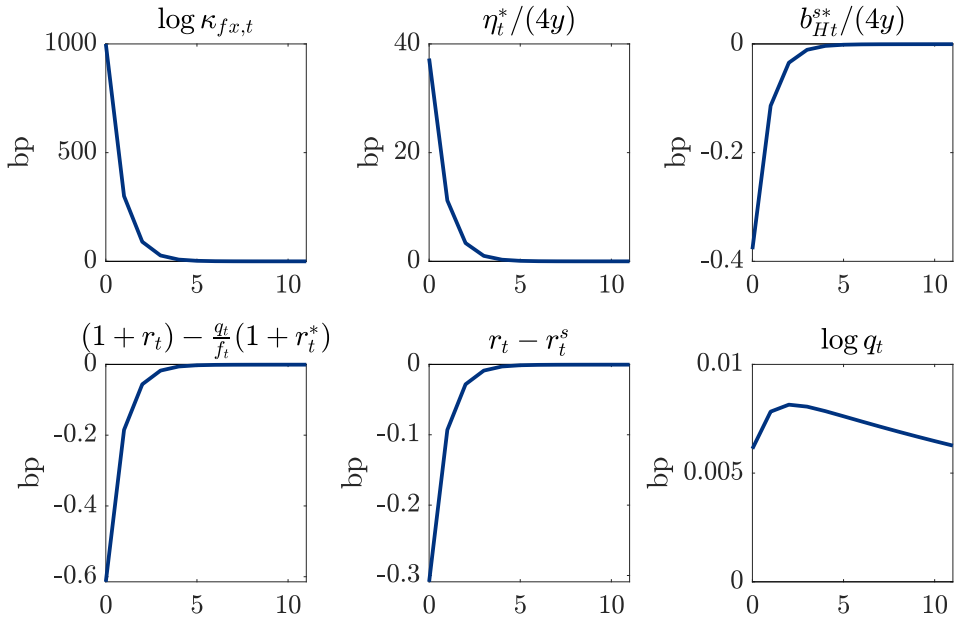


Figure 38: effects of shock to $\log \kappa_{fx,t}$

Notes: $\log \kappa_{fx,t}$ assumed to follow AR(1) process with persistence 0.3.

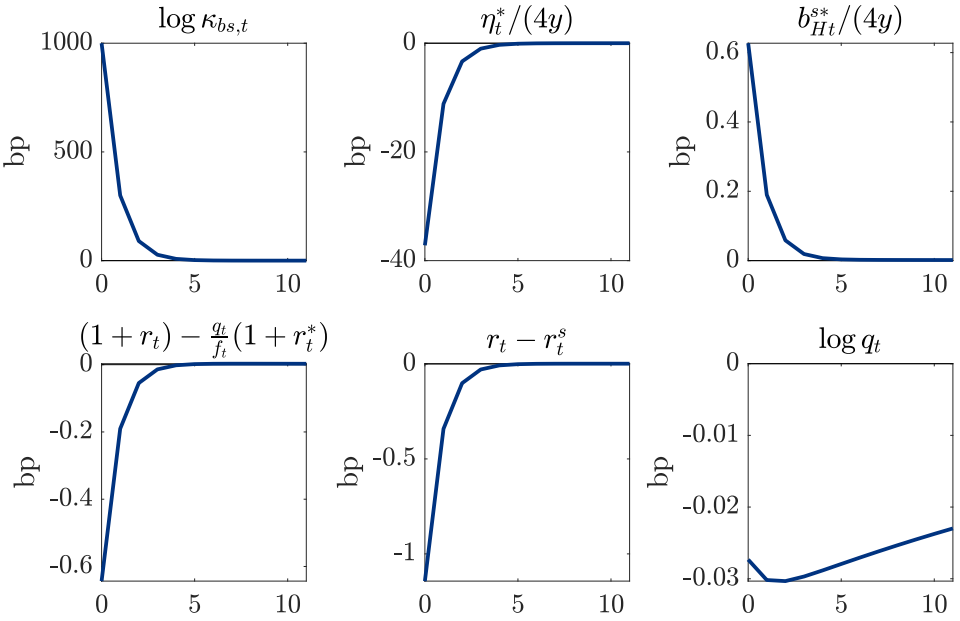


Figure 39: effects of shock to $\log \kappa_{bs,t}$

Notes: $\log \kappa_{bs,t}$ assumed to follow AR(1) process with persistence 0.3.