Central Banker to the World: Foreign Reserve Management and U.S. Money Market Liquidity[*]

Ron Alquist, R. Jay Kahn, and Karlye Dilts Stedman

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Abstract

We show theoretically and empirically that the dollar's status as the global reserve currency exposes U.S. money market liquidity to the foreign countries' real net export shocks. We develop a model in which U.S. money market spreads respond to foreign central banks' exchange-rate management decisions, which are driven by shocks to their net export position. In response to an increase in export-price volatility, foreign central banks remove liquidity from U.S. money markets and cause spreads to widen by selling Treasuries to supply liquidity to their financial systems. Regression analysis shows that shifts in the central banks' demand for dollar liquidity related to oil price volatility are associated with elevated spreads in domestic money markets. A one-standard-deviation increase in the demand for dollar liquidity by a central bank in an oil-exporting country leads to a two to six basis point increase in spreads and an average of $3B in Treasury sales. Consistent with our model's predictions, higher oil-price volatility also induces deposits with the Federal Reserve to rise.

Keywords: Treasury market, repurchase agreements, market liquidity, liquidity premium, exorbitant privilege, fixed exchange rate regime.
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[*] Ron Alquist, Financial Stability Oversight Council (ron.alquist@treasury.gov), R. Jay Kahn, Board of Governors of the Federal Reserve System (jay.kahn@frb.gov), and Karlye Dilts Stedman, Federal Reserve Bank of Kansas City (karlye.stedman@kc.frb.org). The views and opinions expressed in the paper are the authors' own and do not necessarily reflect those of the Financial Stability Oversight Council, the U.S. Department of the Treasury, the Federal Reserve Bank of Kansas City, or the Board of Governors of the Federal Reserve System. We thank Rashad Ahmed, Adrien d'Avernas, Stephanie Curcuru, Reinhard Ellwanger, Lutz Kilian, Colin Weiss, Manjola Tase, Zhaozhao He, and seminar participants at the Office of Financial Research, the Federal Reserve Bank of Kansas City, American University, the 2022 Federal Reserve System Energy Meeting, the 2022 Federal Reserve System Committee on Financial Institutions, Regulation, and Markets meeting, the 53rd Annual Conference of the Money, Macro and Finance Society, and the Federal Reserve Conference on the International Role of the Dollar for their comments and suggestions.

1 Introduction

The U.S. Treasury market is the world's deepest and most liquid asset market and lies at the center of the U.S. and global financial systems. In recent years, however, several episodes of significant deterioration in Treasury and money market liquidity have led to dysfunction in certain market segments. Those episodes occurred in both stressed and benign market environments, raising questions about the economic forces contributing to the market's illiquidity and disruptions in its functioning.

In this paper, we examine a new source of illiquidity – demand for dollar liquidity by foreign central banks. The dollar's use as a reserve currency exposes U.S. money markets to the effects of fluctuations in real terms of trade shocks through foreign reserve managers' portfolio decisions. We develop a model where, in response to an increase in net-export volatility, foreign central banks demand increased dollar liquidity, selling Treasuries and holding more liquid deposits with the Fed for precautionary purposes. We then use the model's predictions to discipline a regression analysis and identify the effect of shifts in foreign central bank Treasury demand on U.S. money market liquidity from 2009 to 2020. In the empirical analysis, we focus on Treasury sales by central banks in oil-exporting countries that peg their currencies to the dollar, which confers two advantages. First, official holdings are likely to make up the vast majority of total Treasury holdings by oil-exporting countries. And second, oil exporters with fixed exchange rates exhibit a predictable and readily characterized relation between oil-price fluctuations, exchange rate changes, and Treasury holdings. In this way, we provide credible estimates of the size of the effect of the portfolio decisions of foreign reserve managers on U.S. liquidity, providing a direct link between this source of illiquidity in U.S. money markets and the dollar's status as the global reserve currency.

Our motivation for homing in on foreign central bank Treasury transactions comes from September 2019 and March 2020, the leading examples of Treasury and money market illiquidity since the 2007/08 financial crisis. In September 2019, a surge in Treasury sales by foreign official accounts preceded a dramatic repo spike, when rates rose from 2% to 10% overnight. Duffie (2020), Barth and Kahn (2020), Vissing-Jorgensen (2021), Banegas et al. (2021) and Weiss (2022) find that foreign official accounts were one of the significant sources of illiquidity in the Treasury market during the March 2020 market stress associated with the COVID-19 pandemic. Similarly, Vissing-Jorgensen

(2021) and Banegas et al. (2021) estimate that foreign official accounts were the second-largest sellers of U.S. Treasuries after mutual funds. Foreign official accounts sold $147 billion in Treasuries, of which foreign central banks accounted for over $100 billion in sales.

Additionally, much of the proceeds from those sales went toward increased holdings of more liquid assets, such as the Federal Reserve's foreign repo pool. Therefore, foreign central banks' behavior during the COVID crisis resulted in a rebalancing of foreign reserve managers' portfolios from less liquid to more liquid assets. The rebalancing affected U.S. money market liquidity directly and indirectly. The direct effect was related to the larger quantity of Treasuries domestic dealers took onto their balance sheets due to their role as market makers in the Treasury market. The indirect effect relates to a reduction in dealers' reserves available to fund Treasury purchases.

Foreign official institutions sold such a disproportionately large quantity of Treasuries in March 2020 because of the dollar's status as the global reserve currency – the United States' so-called exorbitant privilege. Although the term's meaning has varied since the French finance minister Valéry Giscard d'Estaing coined it in the 1960s, we interpret it as the United States' ability to make equity and direct investments abroad and finance those investments by supplying global dollar liquidity (Gourinchas and Rey, 2007). According to this view, the United States acts as the global provider of safe and low-yielding financial assets to market participants with a preference for liquidity (Bernanke, 2005). Thus, the Federal Reserve is the world's central banker as it must consider the foreign central bank demand for liquidity in its reaction function to manage domestic liquidity conditions.

September 2019 and March 2020 provide concrete examples of the spillover effects of foreign reserve management on U.S. money markets and demonstrate how real shocks that influence foreign reserve managers' decisions can propagate to short-term funding markets in the United States. They are, however, stark and extreme examples of how the Treasury market's structure can be vulnerable to specific shocks. In the case of March 2020, it is hard to imagine how even the deepest and most liquid market could successfully reconcile the extreme imbalance between the private and official entities that wanted to sell Treasuries and those that wanted to buy them at that time. By focusing on such episodes of one-sided selling pressure, there is the risk of drawing conclusions that only apply to those cases and do not generalize to more typical circumstances. Further, although we have estimates of the size of the sales and directly observe that they correlate with reductions in U.S. money market liquidity, our current understanding lacks a reliable estimate of the size of the effect of foreign central bank sales on Treasury market liquidity. Our paper aims to characterize the role of liquidity demand from central banks on money markets and provide direct evidence on the size of this effect using a credible identification strategy and as long a time series as possible.

To provide systematic, causal evidence that foreign central banks affect U.S. liquidity through their portfolio choices, we propose a new instrument to isolate the effect of liquidity demand by foreign central banks – option implied oil-price volatility. Our identification strategy relies on independent evidence indicating that, for geological and technological reasons, the oil supply is highly inelastic in the short run, specifically at the daily and weekly frequencies we consider. Therefore, demand shocks and news are the more likely drivers of high-frequency changes in oil prices and oil volatility. Both are plausibly exogenous with respect to reserve managers' decisions. Additionally, we include a comprehensive set of control variables in the regressions to eliminate possible violations of the exclusion restrictions, including news about oil supply derived from OPEC announcements, changes in margins, the credit risk of oil-producing countries, and macroeconomic news, among other factors. This identification strategy can be applied to studies of foreign reserve demand and studies of liquidity in the U.S. Treasury and repo markets, where exogenous variation in liquidity demand is challenging to establish credibly.

We thus focus on oil-producing countries with pegged exchange rates and construct a sample of countries with predictable responses to changes in their oil exports. As oil volatility increases, the central banks of the oil-exporting countries in our sample sell Treasuries and hold more deposits for precautionary purposes, consistent with the model's conclusions. These portfolio decisions coincide with widening interest-rate differentials with the United States, providing further support for our explanation. The liquidity demand of these foreign central banks associated with an increase in oil volatility causes spreads in the U.S. repo market to rise substantially. Thus, in the absence of observable dollar liquidity demand, our model enables us to characterize the incentive for that demand using a directly observable variable. With a high-frequency proxy for reserve management pressure in hand, our focus on oil exporters with a fixed exchange rate provides a plausibly exogenous force driving that pressure in the form of oil price volatility. We find that a one standard deviation increase in interest rate deviations caused by increases in oil volatility leads to a two to six basis points increase in spreads in overnight money markets. Finally, we also provide evidence that the mechanism through which these demand shifts affect U.S. liquidity mirrors the model's logic.

These findings underscore the rationale for the Federal Reserve to provide liquidity to foreign central banks. Our work, therefore, relates to research examining how strains in global dollar funding markets manifested themselves in March 2020 and how policymakers can mitigate the effects of those strains, such as McCauley and Schenk (2020), Goldberg and Ravazollo (2021), Aizenman et al. (2022), Bahaj and Reis (2021), and Ferrara et al. (2022). In particular, Choi et al. (2021) discuss the introduction of the Foreign International Monetary Authorities (FIMA) Repo Facility in March 2020 as part of the Federal Reserve's package of facilities to alleviate the dislocations in Treasury and money markets. Our paper provides an intuitive theoretical justification for the facility. Foreign central banks sell less liquid Treasuries and purchase more liquid assets as a precautionary response to an increase in net-export volatility, thereby reducing the amount of dollar liquidity available to the U.S. private sector. This response allows foreign central banks to avoid the costs of meeting settlement demand for dollars. Introducing a FIMA repo facility into the model reduces foreign central banks' precautionary demand for dollar liquidity by lowering the cost of securing settlement balances for the foreign central bank, increasing U.S. liquidity. The facility also reduces the passthrough of increases in net-export volatility in the foreign economy to U.S. liquidity. In sum, our paper supports the idea that it is in the Federal Reserve's interest to provide facilities that allow foreign reserve managers to easily secure dollar liquidity, given its responsibility for maintaining orderly U.S. money markets.

Foreign central banks' precautionary demand for U.S. dollars is also the topic of Das et al. (2022). That paper studies how stricter ex-ante financial regulations reduce the externality associated with non-U.S. central banks holding inefficiently large amounts of U.S. dollar reserves to mitigate the risks of a domestic financial crisis. By contrast, we focus on how the precautionary demand for dollars can act a conduit for transmitting liquidity shocks to U.S. money markets.

Our paper is also related to work examining the relation between foreign Treasury holdings and Treasury prices (Bernanke et al., 2004; Warnock and Warnock, 2009; Bertaut et al., 2012; and Wolcott, 2020). This research generally focuses on foreign holdings' impact on Treasury yields. For example, Warnock and Warnock (2009) and Wolcott (2020) find that greater foreign demand for Treasuries is associated with lower yields. By contrast, our paper concerns the impact of foreign sales on U.S. domestic liquidity when foreign central banks demand liquidity by selling their Treasury holdings. In this way, we turn the usual question about the effects of dollar illiquidity on emerging-market economies (EME) on its head. Rather than asking how market stress affects liquidity conditions and monetary policy in EMEs, we ask how foreign reserve management policies in EMEs can amplify funding illiquidity in U.S. money markets and lead to responses by the Federal Reserve. Put differently, we study how foreign real shocks propagate to the U.S. financial system and the implications of this transmission channel for macroprudential policy.

The two-country model we develop to guide our empirical analysis builds on other research relating capital flows to exchange rate movements in the presence of financial frictions, going back to Krugman (1999), Aghion et al. (2004), and Blanchard et al. (2005). In particular, we study the role of financial frictions on the exchange rate and capital flows, similar to Gabaix and Maggiori (2015), Akinci and Queraltó (2018), and Bianchi et al. (2021). Our model is closest to Bianchi et al. (2021). Unlike that paper, however, we focus on the foreign central bank's portfolio problem and how it responds to terms-of-trade shocks. The model links the real exports of the foreign country to U.S. liquidity through the portfolio decisions of reserve managers. These portfolio decisions are non-trivial because of financial frictions on international intermediaries in the form of intra-day management of reserves as in Poole (1968), d'Avernas and Vandeweyer (2020), and Bianchi and Bigio (2022). Liquidity premia arise endogenously in the model as a response to the supply of reserves in the United States and the foreign economy. When the central bank faces an increase in net-export volatility, it sells Treasuries but simultaneously demands dollar liquidity to provide dollar buffers to domestic banks. This mechanism can lead to sharp rises in dollar rates as dollar liquidity decreases. The model thus delivers predictions on the effect of terms-of-trade shocks and increases in the volatility of the terms of trade on the central bank's demand for dollar liquidity, which affects U.S. liquidity.

In the next section, we discuss the Treasury sales by foreign official accounts in March 2020, the motivating example for our analysis that starkly illustrates the economic mechanism we have in mind. In Section 3, we document several stylized facts about foreign exchange reserve management in select oil-exporting countries. We develop the model in section 4. In section 5, we discuss the assumptions behind our empirical framework and report the evidence from the regression analysis. Section 6 concludes.

2 Motivation: sales by foreign official accounts in March 2020

As Duffie (2020), Schrimpf et al. (2020), Barth and Kahn (2020), and Vissing-Jorgensen (2021) discuss, March 2020 saw an unprecedented dash for cash in Treasury markets. Bid-ask spreads for off-the-run Treasuries rose sharply across maturities as shown in Figure 1, rising the most for longer-duration Treasuries. Correlations between equities and Treasuries broke down, and Treasury option-implied volatility reached levels higher than those at the peak of the financial crisis. As Treasury market illiquidity increased, so did repo market illiquidity. Spreads and tiering in the repo market spiked.

Several studies point to large sales from foreign and domestic real money investors, particularly foreign central banks and domestic mutual funds, as significant participants in the dash for cash. Pastor and Vorsatz (2020) examine sales by domestic mutual funds. Like us, Weiss (2022) highlights the outsized role oil producers and foreign official accounts played in the dash for cash. In particular, Treasury International Capital (TIC) System data show that net decreases in foreign Treasury positions were around \$257 billion in March, with a decline of \$147 in foreign official accounts.[1] Data from the Federal Reserve's Factors Affecting Reserves, which provide a higher-frequency view of foreign official custody holdings with the Federal Reserve, indicate that these sales began in the last weeks of February, as shown in Figure 2. In all likelihood, these foreign central banks engaged in these sales to build dollar buffers for currency interventions and spending. The Federal Reserve's subsequent implementation of swap lines allowed some foreign official accounts to build the buffers without more significant Treasury sales, though not all countries have access to those swap lines. Treasury sales by foreign official accounts were concentrated in longer duration off-the-run bonds, where liquidity problems in the Treasury market were the greatest. Sales of long-term Treasuries by foreign investors totaled \$250 billion or around 97% of total sales and \$124 billion (84%) of sales by foreign official accounts. Table 1 presents statistics on sales in March for the entire TIC sample and groups of countries of particular interest.

Sales from foreign official accounts stand to influence Treasury market illiquidity for specific

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[1] Unlike other figures from TIC, these figures, which come from the Major Foreign Holders of Treasuries data, are likely to exclude hedge funds domiciled abroad.

institutional reasons. Not only are primary dealers required to make reasonable markets for sales of Treasuries by these accounts, but, as Figure 2 shows, the funds from those sales seem to have been invested in the Federal Reserve's foreign repo pool to a significant extent. Figure 3 outlines the chain of transactions. When a domestic agent sells Treasuries to a dealer and invests the proceeds in a domestic bank account, the funds may still be available to the dealer to fund the Treasury purchase through the repo market. But when a foreign seller invests the proceeds of a sale into the foreign repo pool, reserves are effectively removed from the system, potentially making repo financing of Treasuries more expensive. Although the significant increases in reserves provided by the Federal Reserve probably mitigated the effect of the foreign repo pool on funding availability at the margin, the pool can nevertheless adversely affect Treasury liquidity by making repo balances more expensive.

In particular, in Figure 4 we show foreign-official Treasury sales as measured by weekly changes in foreign official custody holdings of Treasuries with the New York Fed along with the spread of the Secured Overnight Funding Rate (SOFR) over the interest rate on excess reserves (IOER). As can be seen, early in March 2020, as foreign Treasury sales started to increase, liquidity premia in the repo market also began to increase as rates rose above the IOER. As Barth and Kahn (2021) highlights, repo rates becan to decrease following the Federal Reserves expansion of the repo facility and resumption of Treasury purchases on the March 15. Meanwhile, Treasury sales by foreign reserve managers decreased following the creation of the FIMA repo facility on March 31, which allowed these reserve managers to temporarily convert Treasuries to cash at will through repo transactions.

In March 2020, the most significant sales did not come from the two largest holders of Treasuries, China and Japan, but from Saudi Arabia. Figure 5 shows the sizes of sales in March by country, ranked from the largest seller to the largest purchaser. Other oil-exporting countries, such as the United Arab Emirates, Kuwait, Oman, Iraq, and Bahrain, were also large sellers. These countries sold \$39.3 billion in Treasuries, of which Saudi Arabia alone sold almost \$25 billion. By contrast, China and Japan together sold only \$6.6 billion. Although these TIC sales include sales from foreign official accounts and private holders of Treasuries, the oil exporters' central banks and other official accounts likely dominated the amount of Treasuries sold in March. For a sense of scale, if all the sales were foreign official accounts, these six countries would account for almost

30% of total foreign official sales.

In Table 2, we formalize this insight by merging data on oil production per capital from the Energy Information Administration with the data on total Treasury sales. We then divide countries into those with no oil production and equally sized bins of low, middle, and high oil production per capita. For each of these bins, we then calculate total sales of long-term Treasuries and average sales by countries within a bin. High oil production per capita countries sold the largest amount of Treasuries at $102 billion, significantly higher than the low or middle oil production per capita bins. Moreover, the average sales of long-term Treasuries by high oil production countries are over twice those of middle oil production countries.

However, the countries with no oil production were the second highest sellers of total long-term Treasuries, which is unsurprising. Countries sold Treasuries for various reasons in March 2020. In the third column, we adjust the average sales data to account for countries' other reasons for selling Treasuries. In particular, we regress long-term Treasury sales by country on dummies for low, middle, and high oil production and controls for two further reasons to sell Treasuries. We control for countries that are hedge-fund domiciles (Bermuda, British Virgin Islands, Cayman Islands, Ireland, and Luxembourg), as Vissing-Jorgensen (2021) does. Hedge funds sold large amounts of Treasuries in March 2020, and many of those hedge funds were domiciled in those countries.[2] Although the Major Holders of Foreign Treasuries data should exclude hedge funds owned by U.S. investors but domiciled abroad, they may still include hedge funds with foreign investors and other investors seeking preferential tax treatment. We also include a dummy for East Asian countries (China, Hong Kong, Macau, South Korea, Taiwan, Thailand, and Vietnam) whose sales may have decreased because of falling production, as Weiss (2022) suggests. Finally, we control for gross domestic product to capture the differences due to the scale of the economies.

After controlling for these factors in the regression, the results in the third column suggest that countries without oil production are slightly higher than low oil production economies but well below high oil production economies. As Table 1 shows, high oil production economies also sold more than each of the other groups in the aggregate and made up 40% of total sales in March. These results motivate our focus on the determinants of sales by large oil producers.

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[2] See Schrimpf et al. (2020), Barth and Kahn (2021), and Kruttli et al. (2021) for more details on those sales by hedge funds.

These results are consistent with the channel this paper proposes. Foreign official accounts, especially those with dollar pegs who faced increased volatility in net exports due to the pandemic, sold Treasuries and built up more liquid assets such as deposits with the Federal Reserve or domestic banks, which then decreased liquidity in repo markets and Treasury markets. However, this evidence is by no means dispositive. First, a broad range of investors such as mutual funds, hedge funds, foreign official accounts sold Treasuries in March 2020, which makes identifying the effect of portfolio management by reserve managers difficult. Even among foreign accounts, there are reasons that these accounts could have sold other than their demand for liquidity associated with net exports, such as margin calls on dollar investments or fears that the Treasury market would cease to function. Second, the Federal Reserve's introduction of different liquidity facilities and actions by other regulators coincided with these market dislocations. Finally, from March 2020 alone we cannot establish whether the lack of portfolio liquidity was an isolated event or is a more systematic exposure of U.S. money markets to the reserve managers' portfolio decisions. As a result, through the rest of the paper we establish some stylized facts about reserve management by oil exporters, use them to establish a more general model linking reserve manager portfolio decisions to money markets, and then use a model to obtain identifying assumptions to examine this channel empirically.

3 Stylized facts on reserve management by oil exporters

In this section, we investigate the relation between exchange rates, the current account, and foreign official Treasury sales. Motivated by events during the Coronavirus pandemic, we focus on countries with a pegged exchange rate and substantial oil exports. Our focus on countries with an exchange rate peg to the dollar is partly for convenience, as the explicit policy goal of an exchange rate peg makes it easy to discuss the needs for exchange rate interventions. Table 3 lists the countries in the TIC holdings data with pegged exchange rates, as classified by the IMF's 2020 Annual Report on Exchange Arrangements and Exchange Restrictions. The second column lists countries classified as oil exporters by the Treasury. The remaining countries with dollar pegs are predominantly Caribbean banking centers, except for Belize, which provides many banking services for U.S. clients. Since we are interested in Treasury sales induced by export movements, we focus on oil exporters.[3] For the empirical analysis, we restrict the sample to countries with an active forward exchange rate market, which excludes Iraq. These restrictions leave us with five countries: Bahrain, Oman, Qatar, and Saudi Arabia. Table 4 provides summary statistics for these economies across various characteristics. By some measures, these economies are broadly similar. Net exports as a percent of GDP are comparable, ranging from 13-30%. On other margins, they differ. For instance, government debt to GDP is only 18% for Saudi Arabia, whereas it is 83% for Bahrain. Similarly, currency reserves for Saudi Arabia are 63% of GDP, whereas they are 10% of GDP for Bahrain.

Beyond these quantitative economic characteristics, these countries all share common features. They are all monarchies and close neighbors geographically, as Figure 6 shows. These five countries constitute the Arabian Peninsula, excluding Yemen and Kuwait, and all belong to similar international organizations, including the Arab League, Organization of Islamic Cooperation, and the Gulf Cooperation Council.[4] Additionally, before 2016, all five were grouped in the TIC data along with Iran, Iraq, and Kuwait under an aggregate labeled "Asian Oil Exporting Countries" by the Treasury. Further, Saudi Arabia and the United Arab Emirates are OPEC members, while Bahrain and Oman are not, though they sometimes participate in OPEC initiatives, and Qatar's membership in OPEC lapsed in 2019. Across various economic and political characteristics, these countries then form a sensible group for comparison.

3.1 Exchange rate management

Although all five countries in the sample have exchange rate pegs, one key question is how well these countries manage their exchange rate in practice. Table 5 presents the official pegs for each country and the distribution of the market exchange rate reported by Refinitiv Eikon from November 1990 to October 2020. Exchange rates are expressed as local currency per one U.S. dollar. Dur-

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[3] We could, in principle, extend the analysis to other commodity exporters who place some weight on targeting their exchange rates. But it is challenging to find one that permits us to use our identification strategy. Chile is a primary commodity exporter, but it only intervenes in the foreign exchange market sporadically to limit exchange rate volatility (Ilzetzki et al., 2019). Brazil is another plausible candidate for inclusion in the sample as it exports oil, but it is also a major exporter of soy beans and iron ore, making its terms of trade related to shocks that affect those markets. It is important for the validity of our identifications strategy that we are confident what exactly the driving force is that leads to the Treasury sales. That assumption is most likely satisified in the case of countries with fixed exchange rates that are exposed to common shocks that affect demand for their exports and terms of trade.

[4] Only one member of the Gulf Cooperation Council is not included in the data set. Kuwait, a GCC member, pegs to a basket of currencies rather than to the dollar alone.

ing the entire thirty-year period, exchange rates were essentially constant. For the duration and across countries, the 90th and 10th percentiles are never more than 0.002 dollars away from the peg. This evidence suggests that the exchange rate pegs are highly effective and credible.

Although spot exchange rates have stayed close to the official peg, the currencies do experience fluctuations in the forward market. To examine the time-series behavior of the forward rates, we calculate forward exchange rate deviations against the current exchange rate using three-month exchange rate swaps. In particular, we examine:

$$x_{i,t,m} \equiv \frac{F_{i,t,m}}{e_{i,t}} - 1 \tag{1}$$

where $F_{i,t,m}$ is the m-month forward exchange rate for country i at time t and $e_{i,t}$ is the spot exchange rate. We refer to $x_{i,t,m}$ as the implied interest rate differential, and it has some useful properties. Under covered interest parity:

$$x_{i,t,m} = \frac{r_{i,t,m} - r_{\text{USD},t,m}}{1 + r_{\text{USD},t,m}} \approx r_{i,t,m} - r_{\text{USD},t,m}$$

where $r_{i,t,m}$ is the currency i return on an m month risk-free asset. Further, under uncovered interest parity and with no expected revaluations of the currency, $x_{i,t,m}$ is zero.

We construct the empirical counterpart to the forward exchange deviations using exchange rates and 3-month forward exchange rates from Eikon. The panel spans from 2005 to 2021. We annualize the exchange rate differences to obtain implied interest rate differentials. In Table 6, we present the empirical distribution of these differentials. Although the median of the differentials is near zero, for some countries, there is a wide range. In particular, the United Arab Emirates' differentials range between -7% and 4%, while Oman's differentials range between -4% and 5%. The largest deviations occur during the financial crisis and the Coronavirus crisis. Dropping the 2007 to 2009 period and the first and second quarters of 2020 eliminates the largest deviations across countries, though maximum differentials of as much as 4% remain.

In Figure 7, we present the time series of these differentials normalized by their standard deviation. Several commonalities are evident. All series had large deviations during and immediately following the 2007-2009 financial crisis. Further, oil deviations increased dramatically during the

2010s oil glut, when between June 2014 and January 2016, Brent oil prices fell from $111.03 per barrel to $33.14 per barrel. Finally, for several currencies, differentials also increased in 2020, most notably for Oman.

Interest rate differentials are also highly correlated across countries, as Table 7 shows. The lowest correlation between any two countries is 47% between the United Arab Emirates and Oman, and most correlation coefficients are above 60%. We take the first principal component of these five countries' normalized forward deviations to reduce the effects of minor errors in the spot exchange rates and exploit the common component across countries. The first component explains 69% of the daily variance in deviations, and its magnitude is insensitive to excluding episodes such as the financial crisis.

There are two interpretations of what these implied interest rate differentials represent under covered interest rate parity. First, they could represent deviations from uncovered interest rate parity. In particular, divergences between the 3-month risk-free rate in one of the sample countries and the 3-month risk-free rate in the United States. Second, they could represent speculation on low-probability revaluations of the country's currency. In our model, we adopt the former interpretation and show how the interest rate differentials are related to financial flows and the availability of foreign and domestic liquidity when intermediation is constrained and thus linked to Treasury sales and the current account. Even under the interpretation that such deviations represent expectations of revaluations, we still expect them to correlate with Treasury sales to defend the peg and oil price movements that might make such a revaluation necessary. We document these correlations next.

3.2 Exchange rates, Treasury sales, and oil prices

The evidence from March 2020 and the time-series behavior of the forward exchange deviations motivate our analysis of the empirical relation among oil prices, implied interest rate differentials, and oil exporters' Treasury sales. We first construct a series of Treasury sales by these five countries by summing their Treasury positions as reported in the Treasury International Capital System Major Foreign Holders data set. In addition to the first principal component of interest rate differentials across countries in the sample, we also use oil option implied volatility for Brent crude oil, derived from at-the-money options.

We start with the relation between implied interest rate differentials and oil volatility on a country-by-country basis. Table 8 shows the results. We calculate the daily correlation coefficient for each country between option-implied oil volatility and interest rate differentials and regress interest rate differentials (in basis points) on option-implied oil volatility from 2012 to 2021. Despite the daily frequency at which the data are sampled, the correlation coefficients range from 11% to 30% across the specifications. The estimated coefficient associated with oil volatility is statistically significant and positive, implying higher oil volatility correlates with higher interest rates in oil exporters relative to U.S. rates. We also examine the daily relation with the first principal component. The first principal component correlates highly with the individual countries' exchange rates, which is unsurprising given the high correlations among exchange rates. There also is a 30% correlation with option-implied Brent volatility at a daily frequency and a statistically significant relation between the two series in a regression.

In Figure 8, we examine the relation among oil volatility, interest rate differentials, and Treasury sales from 2012 to 2022. Each series is standardized to have mean zero and unit standard deviation in the sample period to permit comparison of the series. The three series appear to be closely related. Periods of high volatility in oil markets such as June 2014, January 2016, and March 2020 are associated with relatively high implied interest rate differentials and extended periods of large Treasury sales by these countries. At monthly frequency, the correlation coefficient between interest rate differentials and option-implied Brent volatility is 72%, while the correlation coefficient between the first principal component and Treasury sales is 52%. These figures suggest a strong statistical relation among the three series.

The figure points to a consistent relation between oil price volatility, forward exchange deviations, and Treasury sales. However, we need to build a structural framework to interpret this relation and its effects on domestic liquidity. We, therefore, present a model that provides an interpretation of the structural mechanisms underlying these relationships. We then use those relationships to examine the connection between foreign official accounts sales and U.S. liquidity.

4 Model of foreign reserve management and dollar liquidity

We develop a two-period, two-country model to relate the different stylized facts to each other and highlight the economic channels that connect them. There are three main actors in the model – an oil exporter, the United States, and international banks that intermediate financial flows between the two countries. The oil exporter and the United States each have a representative household and a central bank. The household in the oil-exporting country owns the oil wells that produce the oil it and the U.S. consumer demand. The oil exporter's central bank pegs its exchange rate to the dollar. The United States produces the consumption good. The fixed number of wells and consumer demand determine the oil price, subject to taste shocks determining the oil exporter's net exports.

Standing between the oil exporter and the United States is a continuum of international banks that intermediates their financial flows. The international banks accept deposits from the oil exporter and the United States and use them to purchase the oil exporter's and U.S. reserves and invest them in U.S. Treasuries. The international banks pass on profits to the oil exporter's household that, for simplicity, owns them. When deciding whether to hold reserves or Treasuries, banks face deposit requirements in the oil-exporting country and the United States that lead to liquidity premia reflected in the returns on reserves. The deposit requirements are thus the financial friction in the model that gives rise to the demand for dollar liquidity.

4.1 Oil Exporter and U.S. Households

We assume that the two periods in our model are on a short enough time horizon that consumers in the oil exporting country and abroad have a inelastic demand for oil producer denominated deposits ($D_t = \bar{D}_t$) and domestic deposits ($\tilde{D}_t = \tilde{D}$) that are invested through an intermediary. The U.S. household can also hold Treasuries directly in quantity $\tilde{B}_t$, but has a demand curve:

$$y_t = \frac{1}{\beta}(1 - v(\tilde{B}_t))$$

Meanwhile, net exports are a random variable $\text{NX}_t \sim N(0, \sigma_Z)$, and the consumer in each country is subject to lump-sum taxes τ_t, $\tilde{\tau}_t$ used to fund each government. In Appendix A, we consider conditions necessary on consumers in the United States and the oil producing country necessary for these assumptions to hold in general equilbrium, however these are not the main mechansims of interest in our model so we move on to a discussion of the financial sector which faces the inelastic demand for deposits from these two consumers.

4.2 International banks

A continuum of international banks indexed on the interval $[0, 1]$ intermediates between the oil exporter and the United States. Each bank has a U.S. headquarters and a subsidiary in the oil-exporting country, over which it makes decisions jointly. The banks are open in the morning and the evening. In the morning, the oil-exporting subsidiary takes domestic deposits D_t, while the U.S. headquarters takes U.S. deposits, $\tilde{D}_t$. The bank then decides whether to allocate the funds from deposits to oil exporter's reserves, M_t, U.S. reserves, $\tilde{M}_t$, or holdings of U.S. Treasuries, B_t.

Intermediaries face an intra-day liquidity problem, similar to Poole (1968), d'Avernas and Vandeweyer (2020), Bianchi and Bigio (2022), and Bianchi et al. (2021). In the evening, three shocks affect the banks. The first two are idiosyncratic deposit shocks Z_t and $\tilde{Z}_t$, both normally distributed with mean zero and standard deviation σ_Z. These shocks reallocate deposits across banks within a country. The third is an independent aggregate exchange shock, S_t, that reallocates deposits between dollars and the oil exporter's currency, which we also assume is normally distributed with mean zero and standard deviation σ_S. During the evening, exchange markets are closed for banks, and banks cannot convert Treasuries to reserves. In the oil-exporting country and the United States, however, banks are subject to the reserve requirement:

$$e_t(\tilde{M}_t + \tilde{Z}_t + \tilde{L}_t) + S_t \geq \theta e_t \tilde{D}_t \qquad M_t + Z_t - S_t + L_t \geq \theta D_t$$

If in the afternoon, the reserve requirement is not met, banks must borrow from the central bank through loans, L_t, which we assume comes at a penalty rate c over the interest rate on reserves for each country. The expected required loans from the central banks in the afternoon give the banks' demand for deposits and reserves in the morning:

$$\mathrm{E}\left[L_t\right] = L(\theta D_t - M_t) = \int_{-\infty}^{\theta D_t - M_t} (\theta D_t - M_t - X) dF(X)\ dX \tag{2}$$

where X denotes the total shock facing F is the cumulative distribution function of the total deposit shock, which is distributed mean zero and variance σ_X, and has a corresponding probability density function f.

The bank balances the cost of the loans against the returns on the various assets it holds. Banks are risk-neutral and live for only one period. These assumptions lead to the maximization problem:

$$\begin{aligned} \mathrm{E}\left[\pi_{t+1}\right] = \max_{B_t, D_t, \tilde{D}_t, M_t, \tilde{M}_t} & \mathrm{E}\left[e_{t+1} y_t\right] B_t + \mathrm{E}\left[e_{t+1}\tilde{\delta}_t\right]\tilde{M}_t + \delta_t M_t - \mathrm{E}\left[e_{t+1}\tilde{r}_t\right]\tilde{D}_t - r_t D_t \qquad (3) \\ & - c\,\mathrm{E}\left[L_t\right] - \mathrm{E}\left[c e_{t+1}\right]\mathrm{E}\left[\tilde{L}_t\right] \\ \text{such that: } & e_t B_t + e_t \tilde{M}_t + M_t = e_t \tilde{D}_t + D_t \qquad (4) \end{aligned}$$

where r_t is the return on the oil exporter's deposits, δ_t is the return on its reserves, $\tilde{r}_t$ is the return on dollar deposits, $\tilde{\delta}_t$ is the return on U.S. reserves, and Y is the return on foreign Treasuries. The constraint in the problem is the morning budget constraint for banks, which reflects their issuance of foreign and domestic deposits, purchases of foreign and domestic reserves, and Treasuries.

4.3 Federal Reserve

For simplicity, we fix the policy of the Federal Reserve. It has a fixed balance sheet $\bar{A}$ that must back both foreign reserve holdings by international banks and the oil exporter's central bank holdings:

$$\bar{A} = \tilde{M}_t + M_t^C \qquad (5)$$

This assumption implies that the Federal Reserve does not respond to shocks that lead to sales by the oil exporter's central bank. In practice, this assumption is most likely satisfied in the short run, which is the time horizon to which the model applies. Over the medium or long run, the Federal Reserve can adjust its reserve holdings.

Similarly, we assume that there is an externally determined supply of foreign Treasuries, $\bar{T}$, so that the oil exporter's central bank, international banks, or the U.S. household must hold Treasuries:[5]

$$\bar{T} = B_t + B_t^C + \tilde{B}_t$$

4.4 Oil-exporter's central bank

Our objective is to relate this situation to the asset holdings of the oil-exporting country's central bank. In light of the empirical evidence, we assume that the oil exporter's central bank has access to two assets: U.S. Treasuries it holds in quantity B_t^C and deposits with the Federal Reserve, which it holds in quantity $\tilde{M}_t^C$. These assets back domestic reserves, M_t. The central bank manages its portfolio over these three assets to keep the exchange rate fixed, $e_t = \bar{e}$, and has a target policy rate of $\bar{\delta}$. We model deviations from the target as coming with a quadratic cost $\kappa^\star(\delta_t - \delta^\star)^2$, which results from inflation and employment trade-offs outside the model's scope.

In the first period, the central bank chooses it's level of reserves, Treasury holdings and holdings of deposits with the Fed. These choices carry through to the second period, where, with probability p, the central bank cannot sell Treasuries. In addition, the oil exporting central bank has to worry about two shocks: first, the change in net exports, which realizes in the morning, and second it must meet international banks' demand for domestic loans in the afternoon. This demand, in the aggregate, is equal to S_t because the within-country shocks Z_t and $\tilde{Z}_t$ are mean zero. We assume that to meet this demand, the central bank cannot sell Treasuries but must instead sell reserves or rely on their holdings of deposits with the Federal Reserve. If those holdings are exhausted, as with the international banks, the foreign central bank faces a cost ψ above the rate on U.S. reserves. The cost is analogous to a penalty rate for an emergency loan from the Federal Reserve or another bank or a cost associated with selling other assets to raise dollars in the evening.

This setup implies a budget constraint for the central bank in the morning of both the first period and the second period:

$$\bar{e}B_t^C + \bar{e}\tilde{M}_t^C = \tau_t + M_t + Q_t \tag{6}$$

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[5] One objection to this assumption is that the U.S. market is large relative to the demands placed by the oil-exporting countries. We have two responses to that objection. First, our results persist in sign, if not in magnitude, if we allow for elasticity in the supply of and demand for Treasuries as long as neither is perfectly elastic. Second, as we show in our empirical results, foreign central bank Treasury sales do appear to affect domestic deposit rates. As the evidence from March 2020 shows, such sales can be large relative to the amount of liquidity the U.S. money market provides.

where Q_t^C represents the profits of the central bank on its foreign portfolio after the cost of providing liquidity domestically:

$$Q_t^C = \bar{e}\left[y_{t-1}B_{t-1}^C + \left(\tilde{\delta}_{t-1} + \psi\mathbf{1}(S_{t-1} \geq \bar{e}\tilde{M}_{t-1}^C)\right)\left(\tilde{M}_{t-1}^C - \frac{1}{\bar{e}}S_{t-1}\right)\right] + c\,\mathrm{E}\left[L_{t-1}\right] - \delta_{t-1}M_{t-1}$$

The expression for Q_t^C reflects the realization of the exchange shock S_{t-1}, the profits on the central bank's other U.S. investments, and the cost of borrowing reserves.

In order to maintain the fixed exchange rate target, the central bank must balance the current account and financial account. Adding up all domestic balance sheet constraints requires that:

$$\mathrm{NX}_t = \bar{e}\left(B_t^C + \tilde{M}_t^C\right) - M_t - \bar{D} - (Q_t^C - r_{t-1}D)$$

In essence, the requirement of a fixed exchange rate pins down taxes by the central bank, which act to hold marginal utilities of consumption between the United States and the oil producer constant. With deposits fixed by consumer demand, when net exports fall, the oil producer must decrease their holdings of U.S. assets or increase their supply of reserves so that the financial account balances with the current account at the fixed exchange rate.

Given the constraint imposed by net exports, the central bank maximizes it's return on investment while taking into account the cost of providing domestic liquidity and meeting interest rate targets. In period 2, if the Treasury market is liquid, the central bank solves:

$$\begin{aligned} V^U(Q_2) = \max_{B_2^C, \tilde{M}_2^C, M_2} \quad & y_2B_2^C - \delta(M_2)M_2 - \frac{\kappa}{2}(\delta(M_2) - \tilde{\delta}_t)^2 + \tilde{\delta}_2 M_2^C - \chi\int_{s=\tilde{M}_2^C}^{\infty} S - \tilde{M}_2^C dG(S) \\ \text{such that} \quad & \bar{e}\left(B_2^C + \tilde{M}_2^C\right) - M_2 = Q_2 + \tau_2 \end{aligned}$$

The value function in this state is independent of its choice of Treasuries. In the liquid market, Treasuries are fungible with the central bank's other investments.

If the Treasury market is illiquid, the central bank instead solves:

$$\begin{aligned} V^C(Q_2, B_1^C) = \max_{B_2^C, \tilde{M}_2^C, M_2} \quad & y_2 B_2^C - \delta(M_2) M_2 - \frac{\kappa}{2}(\delta(M_2) - \tilde{\delta}_t)^2 + \tilde{\delta}_2 M_2^C - \chi \int_{s=\tilde{M}_2^C}^{\infty} S - \tilde{M}_2^C dG(S) \\ \text{such that} \quad & \bar{e}\left(B_2^C + \tilde{M}_2^C\right) - M_2 = Q_2 + \tau_2 \\ & B_2^C \geq B_1^C \end{aligned}$$

where the final constraint reflects the inability of the central bank to sell Treasuries in an illiquid market. As a result of this constraint, the central bank's decision between Treasuries and reserves in period 1 matters in period 2.

In period 1, the central bank maximizes the expected value of their period 2 return, subject to period 1 net exports and net worth. We assume that there is no exchange shock at time zero, so that the only thing that determines the central bank's choice of Treasuries or deposits with the Fed is their relative expected return in period 2. The central bank's objective at time 1 is therefore:

$$\begin{aligned} \max \quad & \beta p \, \mathrm{E}\left[V_C(N_2)\right] + \beta(1-p) \, \mathrm{E}\left[V_U(N_2, B_1)\right] \\ \text{such that} \quad & \bar{e}\left(B_1^C + \tilde{M}_1^C\right) - M_1 = Q_1 + \tau_1 \\ & Q_2 = \bar{e}\left(y_1 B_1 + \tilde{\delta}_1 \tilde{M}_1^C\right) + c \, \mathrm{E}\left[L_1\right] - \delta_1 M_1 \end{aligned}$$

4.5 Model Implications

In the model's equilibrium, seven markets clear: the oil market, the market for the consumption good, the market for the oil exporter's currency deposits, the market for the oil exporter's currency reserves, the market for U.S. reserves, the market for U.S deposits, and the market for Treasuries. The taste shock ω_t, which we assume is an independent and identically distributed random variable, determines the paths of each of these variables and is the main driving force of the model's dynamics. There are three financial factors, y_t (which reflects the cost of funds), $y_t - \tilde{\delta}_t$ (which reflects U.S. liquidity), and $\delta_t - \tilde{\delta}_t$, which reflects relative liquidity in the oil-producing country. Any asset in the model can be described by these factors. The two liquidity factors reflect the tightness of reserves in the United States and the oil-producing country.

In turn, these factors reflect the settlement frictions that cause the demand for reserves to be segmented between the United States and oil producing countries. In the United States, the deposit market friction means that:

$$y_t - \tilde{\delta}_t = cF(\theta \bar{D} - \bar{A}) \tag{7}$$

where F is the cumulative distribution function of the combined deposit shock to U.S. banks, $\tilde{Z}_t + S_t$. This condition equates the difference between the return on holding Treasuries and holding reserves to the expected cost of reserve short-falls next period, reflecting the additional benefit reserves have in meeting this requirement.

Meanwhile, because U.S. dollars cannot be used to meet oil-producing country reserve requirements means that a different factor is necessary to represent the relative costs of liquidity in the oil-producing country:

$$\tilde{\delta}_t - \delta_t = cF(\theta \bar{D} - M_t) - cF(\theta \tilde{D} - \tilde{M}_t) \tag{8}$$

given the pegged exchange rate, this equation describes a deviation from covered interest parity, which reflects the settlement demand of the intermediary for reserves in each country. As the U.S. rate on reserves increases relative to that in the oil-producing, the intermediary is willing to hold more U.S. deposits and fewer reserves. On the other hand, from the oil-producing central bank's point of view, if U.S. liquidity increases, to keep the exchange rates fixed, the central bank must either tolerate higher interest-rate differentials or supply more reserves domestically. Along with the central bank's commitment to keeping the current account balanced, this equation constrains the oil-producing central bank's decision resulting from the peg.

4.5.1 Precautionary demand for liquidity by foreign central banks

In this environment, the portfolio decisions of the oil-producing central bank matter for liquidity in the United States and the oil-producing country. In response to a decrease in net exports, the central bank must either sell Treasuries, decrease its holdings of deposits with the Fed, or increase its domestic supply of reserves. With a fixed supply of reserves, the oil producers increased holdings of deposits with the Fed leave fewer dollar reserves for the intermediary, driving U.S. liquidity down and domestic spreads up. Decreased supply of domestic reserves mean less oil-producer reserves for the intermediary, driving oil-producing country liquidity down and increasing spreads. Meanwhile, sales of Treasuries by the oil-producing country, when taken on by the intermediary, reduce holdings of reserves both in the United States and the oil-producing country.

The primary implications of the model are that these portfolio decisions by the foreign central bank, induced by shocks to net exports, affect U.S. liquidity. In effect, the oil producing central bank's demand for liquidity removes liquidity from dollar markets. This effect is summarized in the primary theorem from the model, which we derive in more detail in Appendix B:

Proposition 1 *An increase in the volatility of net exportts causes the oil exporter's central bank to sell Treasuries, leading to wider interest-rate differential and U.S. money market spreads as liquidity is drained from the U.S. market.*

This feature of the model results from the oil producing central bank's precuationary demand for dollar liquidity. The oil producing central bank has a desire to have sufficient dollar deposits with the Fed going into the second period to cover their settlement risk in the event that the Treasury market is illiquid. In this event, the central bank would be unable to build sufficient dollar deposits simply by selling Treasuries. The precautionary motive produces the downward-sloping demand curve in Figure 9, since as interest rates on dollar deposits fall relative to Treasuries, the central bank is more willing to face the possibility that they may not have sufficient dollar deposis tomorrow to meet the settlement shock.

Equilibrium occurs where the central banks' willingness to hold dollar deposits with the Fed is equal to the the demand for reserves from the intermediary, since both are splitting the Fed's fixed balance sheet. The upward sloping blue line in Figure 9 represents the total size of the Fed's balance sheet less this demand from intermediaries, which responds to the same U.S. liquidity factor.

As net export volatility increases, the central bank faces greater precautionary demand for reserves. This effect is reflected in the darker shared lines in Figure 9. Higher net export volatility in equilbrium increases the odds that the central bank is left with too few reserves to cover their needs for dollar deposits with the Fed for settlement balances. Simultaneously, U.S. liquidity decreases, as the oil-producing central bank is now holding more dollar deposits meaning there are fewer reserves for the intermediary. As the central bank holds more deposits, for the same level of net exports today, it must either sell Treasuries or issue more domestic reserves. The more weight the oil exporter's central bank attaches to keeping the domestic interest rate at the target in its objective function, the more Treasuries it sells to the intermediary, and the fewer reserves it sells. However, unless the central bank places weight only on its interest rate target, the central bank will not increase reserves by enough to offset the increase in interest rate differentials fully, and as a result interest rate differentials will widen.

4.5.2 The effect of the FIMA repo facility

The model also shows how liquidity facilities such as FIMA repo facility can mitigate the effects of the oil exporter's central bank's demand for dollar liquidity. This facility was introduced by the Federal Reserve on March 31, 2020, allowing foreign official accounts holding Treasuries with the Federal Reserve by borrowing money through repo agreements with the Fed at a prearranged rate. These arrangements were made for a much broader set of countries than swap lines, and aimed at providing temporary liquidity to Treasury holders.

In the context of our model, we can think of the FIMA repo facility as providing an alternative and lower cost way of meeting settlement demand for dollars for the central bank. Assume that this facility occurs at a penalty rate, ϕ above the rate on dollar reserves, with $0 < \phi < \psi$. The FIMA facility therefore dominates the existing technology for securing settlement balances, and therefore the new precautionary demand reflects the lower expected cost of insufficient settlement balances. The resulting demand curve from the oil-producing central bank is displayed in Figure 10 in green. The first result of the introduction of such a facility is clear: the oil-producing central bank will now hold fewer reserves at the same liquidity premium, since they now face a lower cost of settlement balances. As a result, in equilbrium both oil-producing central bank holdings of deposits with the Fed will decrease as will U.S. spreads. Moreover, increases in volatility now have a smaller effect on U.S. liquidity, as the central bank is now less Treasuries. This example indicates the importance of the FIMA repo facility as a solution to the precautionary dash-for-cash among foreign official holders of Treasuries in March 2020.

5 Empirical analysis

5.1 Identification strategy

For the large oil-exporting countries in the sample, the model provides a causal chain from oil shocks to interest rate differentials to Treasury sales that, ultimately, consume dollar liquidity. This chain supplies theoretical structure to the empirical relationships that motivate our analysis. That structure permits us to identify the effects of foreign exchange management by oil exporters on dollar liquidity.

In particular, Correa et al. (2020) has shown that dollar illiquidity in the repo market affects foreign exchange rates by raising arbitrage costs. If borrowing costs in dollar repo markets rise, the returns to arbitrage between the dollar and foreign markets will reflect the higher costs. This relation introduces the possibility of reverse causality between exchange rate fluctuations and changes in repo rates unrelated to the effects of foreign reserve management. For the oil-exporting countries in the sample, however, the model provides a theoretical channel that explains the reason for Treasuries sales in response to oil-price shocks. The framework, therefore, suggests oil price volatility as a natural instrument for exchange rate management by these countries.

One possible objection is that the exclusion restriction required for the oil-price volatility to be a valid instrument is violated. For example, the model does not account for the market power these oil exporters exercise through OPEC to set oil prices. The countries in the sample may make a joint decision about oil production and managing their exchange rate pegs that undermine the credibility of the chain of causation laid out in the model. Additionally, OPEC decisions may affect oil volatility while not providing a shock to exchange rate management because oil producers have ex-ante information about the direction of those changes.

Several independent pieces of evidence cast doubt on the validity of these claims. To start, OPEC has historically been more effective at restricting new capacity growth by limiting efforts to find and develop new oil resources rather than extracting less oil than existing wells can produce (Smith, 2009). The relevant time horizon for developing new oil production capacity is years rather than days or weeks, making it implausible that OPEC decisions would affect the demand for dollar liquidity at the horizons we are considering. Moreover, geological constraints are the primary determinants of an oil well's flow rate once the operator has drilled it, leaving the rate largely outside the operator's control (Newell and Prest, 2019). Thus, the geology of oil production supplies a further justification for postulating that oil production in the model is exogenous, at least over the relevant horizons for our analysis. Finally, Anderson et al. (2018) provide extraneous microeconomic evidence and theoretical results consistent with the idea that the price elasticity of oil supply is close to zero within the month.[6]

Next, although oil producers possess an informational advantage in all aspects of their ability to change oil production and existing capacity, this advantage does not necessarily translate into superior information for oil pricing. Brunetti et al. (2013) show OPEC's so-called fair price pronouncements have little influence on the market price of crude oil. They provide little new information to oil futures market participants, calling into question the assumption that OPEC countries have superior information about oil pricing compared with futures market participants. The absence of an informational advantage makes it less probable that the oil exporters in the sample can forecast the direction of oil prices and volatility and manage their foreign exchange reserves in advance of those changes. In sum, all the evidence points to the validity of the premises of the identification strategy implied by the model.

To address any remaining questions about confounding effects, however, we also construct a daily series of OPEC announcements during the sample period by scraping press releases from the OPEC website based on Känzig (2020). We then construct additional controls based on the returns and the absolute value of returns on those announcement data. We include these variables as controls in the first and second stages of the instrumental variables regression. Given that we use daily data, the announcement variables control for information related OPEC's intentions for future production and supply.

While our use of oil price volatility provides a credible solution to the problem of reverse causality, simultaneity remains a concern in the absence of additional consideration. That is, oil price volatility often reflects market forces acting on oil, reserve management pressures, and treasury markets at the same time. A similar issue lay in the degree to which oil volatility affects the repo market through channels other than that which our model centers. In the most obvious case, U.S. macroeconomic news and associated uncertainty almost certainly play a substantial role in driving high frequency movements in repo spreads and oil price volatility. Moreover, shocks

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[6] See Kilian (2022) for a survey of the econometric issues related to estimating demand and supply elasticities in the crude oil market, with a particular emphasis on structural VARs.

emanating from oil markets (which manifest in option implied volatility) themselves breed uncertainty about the global growth outlook. Our approach to answering these challenges is two-fold. First, while changes in the level of oil prices have a clear link to global growth (i.e., demand) news, option implied volatility in the price of oil has a less predicable relation with oil demand. Second, we control for several factors that may independently affect repo rates, along with factors that plausibly affect both liquidity and oil price volatility at high frequencies (i.e., daily news). To ensure that changes to oil price volatility or repo spreads cannot be attributed to the release of U.S. macroeconomic news, we control for the unexpected component of macro news announcements using the Citigroup Economic Surprise Index.[7] Financial market conditions also potentially confound our causal claim through the same basic channels. Thus we include the VIX index among our controls to account for financial market developments on a given day. Finally, we include a dummy for the dates of FOMC announcements that might represent news relevant to money markets which also clearly carry implications for growth. In the context of our high frequency application, this specification cleanses the instrument of these confounding forces to identify our chosen channel.

One more direct concern would be that oil volatility increasing may raise margins on oil futures contracts. We also control for Brent returns to separate general changes in oil prices from volatility In turn, this could require commodity brokers or other levered fund to meet additional margin requirements by borrowing in the repo market, thereby raising rates. To address this concern directly, we control for margins on the active West Texas Intermediate futures contract, using data from the CME group. This contract is not directly linked to oil exported by the countries in the sample as it is based on U.S. prices. But this contract is the primary oil futures contract traded in the United States and most relevant for U.S. investors' margin exposures.

Finally, we control for CDS premia on Saudi Arabian bonds as a way to capture the affect of default risk on the underlying Saudi debt in the interest rate factor. Including this variable as an additional control separates out the confounding effect of increases in oil-price volatility increasing the risk of default from the its effect on the incentive of oil producers to adjust their reserve holdings.

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[7] In unreported results, we find that including the U.S. daily economic policy uncertainty from Baker, Bloom, and Davis (2016) leaves our results materially unchanged.

5.2 Repo data

We collect a daily series of repo rate spreads, exchange rate differentials, and Brent option-implied volatility to test the implications of our model. Figure 11 presents the various aggregate rates we use to measure repo and money market activity and the transactions to which they apply. The aggregate measures of repo rates include the Secured Overnight Funding Rate (SOFR) and the General Collateral Finance (GCF) repo index. SOFR is a broad measure of repo funding rates that the Federal Reserve Bank of New York maintains. GCF measures inter-dealer general collateral repo rates from the Fixed Income and Clearing Corporations (FICC) cleared tri-party GCF repo service.

We examine the spread of these repo rates over several baseline rates. The spread of SOFR over the interest rate on excess reserves (IOER) is a broad measure of the difference between repo rates and rates that banks receive for holding excess reserves with the Federal Reserve. Next, the difference between the GCF index and the interest rate on excess reserves gives a narrower picture of inter-dealer spreads. Further, the spread between the GCF repo rate and the Tri-party General Collateral rate the Federal Reserve produces captures the difference between inter-dealer funding costs and the costs to dealers of borrowing from institutions such as small banks and money market funds. Finally, the spread between the GCF rate and the effective federal funds rate provides a measure of the difference between secured inter-dealer rates, and the overnight rate banks borrow unsecured from institutions such as the Federal Home Loan Banks. Table 9 reports summary statistics for these various spread measures over the sample period.

5.3 Data on other controls

As several papers have pointed out, repo rate spreads respond to several factors that influence the supply of and demand for liquidity (Correa et al., 2020; Afonso et al., 2020; and Anbil et al., 2021). Therefore, we collect data on daily controls to capture the different determinants of repo rates. These include daily Treasury issuances of notes, bonds, and bills from TreasuryDirect, volumes in the Treasury General Account (TGA) from daily Treasury statements, Federal Reserve purchases of Treasury securities, and volumes in the overnight reverse-repurchase and repo facility. We also include three-month Treasury bill yields from FRED and three-month dollar overnight interest rate swaps from Refinitiv. Finally, we include a dummy variable to capture month-end funding pressure coming from foreign banks' incentives to window dress their positions (Munyan, 2015; and Anbil and Senyuz, 2018) and corporate income tax payment data that capture withdrawals from money market funds.

5.4 Repo rate results

Table 11 displays the results of daily instrumental variables regressions of repo spreads on implied interest rate differentials (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls for other factors affecting the repo rate. Sample sizes differ across the regressions because reference rates constructed by the Federal Reserve (specifically the SOFR and the TGCR) are only available after 2014, while the GCF index goes back to 2005. The differing sample periods lead to two first stages for the IV regression, each shown in Table 10. The first is the short sample for the SOFR-IOER and GCF-TGCR spreads; the second is a long sample for the GCF-IOER and GCF-EFFR spreads. The instrumented variable in these regressions is the first principal component of implied interest rate differential across the five countries. We then set the sign of this component equal to the sign of its loading on exchange rates – all the exchange rate loadings have the same sign – and standardize the variable so that it is mean zero and has a unit variance.

The first stage results of this standardized principal component on instruments and endogenous controls contained in Table 10 are broadly similar across the two samples. We can explain a large share (around 70%) of the first principal component of exchange rate differences in the first stage regressions. As Figure 8 suggests, oil price volatility is a key determinant of interest-rate differentials. It is highly significant even after other endogenous controls are included in the regression. The measure is also responsive to the Treasury bill yield and TGA balances, though the degree of variance these two variables explain is small. CDS spreads have a large effect, consistent with a portion of the interest rate differential being attributable to risk. U.S. macro news and WTI margins correlate with the first stage variable, as do Brent returns in the longer sample. For both sample periods, the instruments are strong, with F-statistics over 350.

To examine the effects of the oil volatility-induced changes in interest-rate differentials on repo spreads, we turn to Table 11, which contains the second-stage results. The first two columns are broad measures of repo market spreads and represent the difference between the repo rates and the rates banks receive from the Federal Reserve. A one standard deviation increase in interest rate differentials leads to a roughly two basis point increase in the SOFR over the interest rate on excess reserves and an approximately five basis point increase in GCF over the interest rate on excess reserves. We compare these measures to the summary statistics in Table 9 to put this estimated coefficient in context. The spread between the 25th and 75th percentile of the SOFR-IOER spread and the GCF-IOER spread is roughly fifteen basis points, meaning that the increases are large relative to the daily history of these rates. Further, a one-standard deviation increase in interest rate differentials would lead to a roughly 0.17 standard deviation increase in the SOFR-IOER spread and a 0.43 standard deviation increase in the GCF-IOER spread. This evidence suggests that exchange rate management by oil exporters has an economically and statistically significant effect on repo spreads.

The third and fourth columns provide additional information on the determinants of these spreads. The GCF-IOER spread compares an inter-dealer repo rate secured by Treasuries to an unsecured rate set by the Federal Reserve and available only to banks. This spread is the closest equivalent to the spread between intermediary funding rates and policy rates in the model. The GCF rate is compared to the effective federal funds rate in column four. This spread represents a market rate primarily constituted of banks borrowing from specific non-bank institutions such as Federal Home Loan Banks, as suggested in Afonso et al. (2013). The results in this column show that a one standard deviation increase in interest rate differentials leads to a roughly 2.5 basis point increase in the GCF-EFFR spread. These results suggest that just under half of the total GCF-IOER response can be attributed to the demand for unsecured funds beyond what is captured in the IOER (EFFR-IOER).

The GCF-TGCR spread in the third column provides a more refined measure of repo market spreads. It compares two overnight rates secured by Treasuries: the inter-dealer cleared tri-party GCF rate and the customer-to-dealer uncleared tri-party rate. Both rates are for general collateral Treasury transactions. However, we can think of the TGCR as primarily representing the rate at which money market funds lend to dealers, while the GCF rate represents primarily the rate that dealers borrow and lend to each other in the repo market.

The regression results show that a one standard deviation increase in the interest rate differential leads to a roughly four basis point increase in this spread. Most of the effect on GCF-IOER spreads consists of differences in funding rates between banks, which can invest at the IOER, and non-banks, such as money-market funds, which do not have direct access to the IOER. This evidence highlights the importance of reserve scarcity and segmentation in the passthrough of shocks from oil prices to the exchange rates of oil exporters and, ultimately, repo markets that the model highlights.

Finally, in Table 12, we present the results of uninstrumented regressions of repo spreads on our interest rate differential factor. The estimated coefficients from these regressions are smaller in magnitude than the instrumented coefficients, suggesting another channel through which higher interest rate differentials are associated with a lower disconnect that our instrument eliminates. One example of such a channel is expectations of U.S. monetary policy easing. Changes in those expectations would lower spreads in the repo market while simultaneously raising the differentials between foreign and U.S. rates if foreign central banks did not immediately respond. In the instrumented regression, Treasury bill yields are more important determinants of rates, suggesting that Treasury bill yields decrease through this channel, as we would expect if the Fed eased monetary policy. The FOMC dates are also generally associated with higher repo rates in the instrumental variables regression but not in the uninstrumented regression.

We conduct two tests to ensure our results are robust to different subsample splits. First, to ensure our results are not driven solely by March 2020, in Table 13, we drop all dates after January 1, 2020, and repeat the instrumental variables regression. The signs and magnitudes remain largely the same as in the full-sample analysis. Our results for the SOFR-IOER spread are no longer significant, however.

Second, in Table 14, we restrict our results to the period from 2015 onward, following the SEC's money market reforms when funding conditions were generally tighter. Our results do not change materially except that the magnitudes of the estimated coefficients associated with the SOFR-IOER and GCF-EFFR spreads increase. Scarcer reserves and changes in the structure of money markets in 2015 may be the causes of this change.

5.5 Validating the model-implied channel

The model identifies a channel through which large oil exporters' interest rate differentials affect U.S. money markets. So far, the results indicate a causal relation between exchange rate movements and repo market spreads. But they are silent on the conduit through which shocks in oil-exporter interest rate differentials spill over to U.S. short-term funding markets. In this section, we investigate which channels transmit the impact of exchange rate deviations on Treasury holdings and domestic reserves. The results suggest that the exchange rate shocks are associated with decreases in Treasury holdings by large oil exporters, which in turn increase the dealers' holdings and, at the same time, reduce reserves available to the dealers to fund Treasury holdings. This chain of causation aligns well with the economic logic we develop in the model.

We begin by examining the relation between interest rate differentials and Treasury holdings. Table 15 displays the results of regressions using the TIC data, which is monthly and therefore provides fewer observations in the estimation. We use TIC data to calculate total Treasury holdings by Bahrain, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. The first column corresponds to the data shown in Figure 8. It suggests that oil-exporting countries' holdings decrease by roughly $4 billion in response to a one standard deviation increase in the first principal component of these countries' interest rate differentials. This evidence is consistent with the model's core logic: oil exporters must sell Treasuries to maintain their exchange rate pegs. The table's second and third columns show that almost all the sales are in the form of longer-term Treasuries, which have a large and statistically significant effect. By contrast, there is no significant effect on short-term Treasuries, leading to an estimated coefficient that is statistically insignificant in the first column. This result is also consistent with what we expect based on the model. The oil exporters' central banks sell less liquid Treasuries because they need the more liquid ones for other reserve operations. The R^2 values for these regressions also suggest that we can explain a substantial portion of holdings with these variables for long-term Treasuries. For short-term Treasuries, the share explained using these variables is smaller.

The second set of three columns in Table 15 focuses on all holdings by foreign official accounts. Although the total Treasury holdings for oil exporters mix foreign official accounts for the exporters and private holdings, the foreign official holdings data mix holdings by oil exporters and other countries but reflect exclusively foreign central banks and other government funds. The overall effect on long-term Treasury holdings is insignificant, suggesting that the impact on Treasury sales is concentrated in oil-producing countries. There is a positive and significant sign on short-term Treasury sales by all foreign official accounts. When we drop March 2020 from the sample in Table 16, oil exporter sales of long-term Treasuries remain statistically significant, and oil exporter sales of long-term Treasuries become statistically significant. But short-term total sales by foreign official accounts cease to be significant, suggesting that this finding is sensitive to the peculiarities of March 2020.

We extend the analysis further by examining the effects of such shocks on U.S. financial institutions and various accounts with the Federal Reserve. We hypothesize that foreign Treasury sales feed into U.S. short-term funding markets by increasing Treasuries with primary dealers, which are required to make reasonable markets for sales by custody accounts with the Federal Reserve, and simultaneously decreasing reserves as the cash held in the foreign repo pool increases. Table 17 reports the regression evidence on this effect by examining the impact on primary dealers and Federal Reserve accounts. We assemble weekly data from the Federal Reserve Bank of New York's Primary Dealer Statistics on net Treasury coupon positions and balances in custody holdings, the foreign repo pool, and swap lines from the Federal Reserve Board's H.4.1. Factors Affecting Reserve Balances release. These accounts are subject to slow-moving trends unrelated to the mechanism we are concerned with, so we control for these trends by removing a 90-day moving average.

The first column in Table 17 suggests that, though insignificant, a one standard deviation increase in interest rate differentials of oil-producing countries is associated with a $3 billion increase in primary dealers' net exposure to coupon Treasuries over the previous 90-day moving average. This estimate is similar in magnitude to the decrease from foreign official accounts on a month-over-month basis in Table 15. The increase in dealers' net exposure to Treasuries suggests that they may be unable quickly to offload the Treasuries they purchase from foreign official accounts. Since many foreign official accounts hold long-duration off-the-run Treasuries for which there is generally limited liquidity, it may be difficult to find immediate buyers. These results are, therefore, broadly consistent with the mechanism we have in mind.

The second, third, and fourth columns examine the effect of the interest rate differentials on

Federal Reserve accounts. The second column shows that the increase in the differentials does not significantly affect custody holdings with the Federal Reserve. The sign remains consistent with the main results, however. Again, the lack of significance may be attributable to the custody accounts mixing short- and long-term Treasuries.

The third column examines the effect of these oil exporter rate shocks on the foreign repo pool. Here the results are consistent with the primary mechanism developed in the model. The regression results indicate that a one standard deviation increase in exchange rate deviations leads to a roughly $5 billion increase in investments by foreign official accounts in the Federal Reserve's foreign repo pool. This finding suggests that foreign exchange management by oil exporting countries decreases the supply of reserves to the rest of the financial system. The foreign repo pool investments lead to lower reserves with banks for the same level of assets held at the Federal Reserve. Investing in the foreign repo pool is a highly liquid investment for foreign central banks. It corresponds to the investment in reserves we include as an option for the central bank in the model.

Another way to obtain dollars for some central banks is through central bank swap lines with the Federal Reserve. The effects of these swap lines have been examined in Fleming and Klagge (2010), Allen et al. (2017), Cetorelli et al. (2020), Eguren-Martin (2020), and Aizenman et al. (2022), among others. The final column of Table 17 looks at the response of the swap facility to a shock to the exchange rates of oil exporters. It shows that there is no statistically significant effect. The absence of any effect on the Federal Reserve's swap lines is easy to explain: the swap lines are only available to a select group of large, developed economies. Following the COVID crisis, the Fed extended the swap lines to Australia, Brazil, Korea, Mexico, Singapore, Sweden, Denmark, Norway, and New Zealand. The oil exporting countries in the sample never had access to those swap arrangements. Therefore, the results in this column serve as a placebo and indicate that shocks to the interest rate differentials of oil exporting countries do not lead to the rebalancing of reserve positions by developed non-oil exporters.

Taken together, the results in this section confirms the primary mechanism developed in the model. They suggest that shocks to exchange rate management by major oil exporters lead to (1) decreases in these countries' holdings of long-term Treasuries; (2) decreases in foreign official holdings of Treasuries; (3) lead to increases in primary dealers' holdings of Treasuries; and (4) decreases in the supply of reserves to these dealers as the proceeds are invested in the foreign repo pool. Thus the results support our core argument – that exchange rate management by foreign central banks removes liquidity from U.S. markets, leading to higher costs of short-term funding in the United States.

6 Conclusion

In the case of oil exporters with pegged exchange rates, foreign reserve management can have sizeable effects on U.S. domestic liquidity. A one-standard deviation increase in the demand for dollar liquidity by a central bank in an oil-exporting country leads, on average, to three billion dollars of Treasury sales and a two to six basis point increase in U.S. money market spreads. This evidence suggests that the dollar's status as the global reserve currency creates a channel through which shifts in foreign official demand for dollar liquidity can spill over to the U.S. financial system and adversely affect short-term funding liquidity conditions. Our model demonstrates how the dollar provides liquidity to foreign central banks that manage their exchange rates. As a result, U.S. money markets may have to absorb large sales of Treasury securities even as foreign official investors drain reserves. We provide regression evidence documenting the effect of these sales on domestic money markets and showing how the sales affect domestic banks, dealers, and the supply of reserves to banks.

In the model's background lies a possible way to mitigate this effect. In a banking system with ample reserves, foreign official accounts are among many demands on the Federal Reserve's balance sheet. In much of the sample period, reserves were relatively scarce. By contrast, in an environment with plentiful reserves, foreign official sales of Treasuries should have a more limited effect on the liquidity of domestic money markets. Given the dollar's widespread use by many developed and emerging market reserve managers, the amount of reserves in the system must accommodate the diverse needs of those different market participants. Our results show these needs extend well beyond large economies with access to the swap lines and beyond traditional large holders of Treasuries such as China and Japan. The international role of the dollar and the resulting global nature of U.S. money markets may therefore require adopting a broader view of liquidity provision during future dashes for cash. In that respect, our findings underscore the importance of liquidity facilities such as the Foreign and International Monetary Authorities (FIMA) Repo Facility as an effective means for reducing stress in global dollar funding markets and preventing adverse spillovers from abroad to U.S. short-term funding markets.

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A Assumptions on consumer preferences

This Appendix outlines assumptions that are sufficient for the starting point of the two-period model that:

1. Deposits are fixed.
2. Net exports are an exogenous function of taste shocks.
3. Taste shocks are positively correlated with oil prices.

These assumptions are not key to the mechanism we highlight in the rest of the paper, but help to provide a general equilibrium framework for our results.

The oil exporter's household obtains utility from consumption, C_t, oil, X_t, and a non-tradable good N_t. It has an endowment of oil wells, W, that produces a quantity of oil W each period and sells it at a globally determined price v_t. The assumption of a constant oil supply matches the frequency of our empirical analysis, which is daily or weekly. Over those horizons, the oil supply is likely to be fixed. The exporter's household also has an endowment of the non-tradable good, H.

Consumers discount at a rate β and maximize the discounted present value of their utility:

$$\sum_{t=0}^{\infty} \beta^t \, \mathrm{E}\left[\frac{1}{1+\omega_t}\log(C_t) + \frac{\omega_t}{1+\omega_t}\log(X_t) + \gamma\log(N_t)\right] \tag{9}$$

where ω_t represents a shock to oil demand that we postulate is exogenous and use to generate changes in oil prices and the current account. The budget constraint is:

$$p_t C_t + v_t X_t + D_t + \tau_t + N_t = v_t W + H + r_{t-1} D_{t-1} \tag{10}$$

where p_t is the price of consumption, v_t is the globally determined oil price, D_t are domestic deposits, τ_t is lump-sum taxes, and r_t is the gross return on those deposits.

For simplicity, we also assume that consumers face a deposits-in-advance constraint:

$$p_t C_t + v_t X_t \leq r_{t-1} D_{t-1}$$

This construction simplifies deposit demand, allowing us to obtain equilibrium in financial markets.

The U.S. household is nearly symmetric in terms of preferences, except that it also demands Treasuries:

$$\sum_{t=0}^{\infty} \beta^t \, \mathrm{E}\left[\frac{1}{1+\omega_t}\log(\tilde{C}_t) + \frac{\omega_t}{1+\omega_t}\log(\tilde{X}_t) + \gamma\log(\tilde{N}_t) + \rho\log(\tilde{B}_t)\right] \tag{11}$$

The U.S. household is subject to the same preference shock of oil, ω_t, as the oil exporter's household. The U.S. consumer's demand for Treasuries represents a dimension of liquidity not captured in the intermediaries' decision problem or as a reduced-form way to create preferred habitat demand.

The U.S. household also faces a different budget constraint represented in terms of the oil exporter's currency:

$$p_t\tilde{C}_t + v_t\tilde{X}_t + e_t\tilde{D}_t + \tilde{\tau}_t + e_t\tilde{N}_t + e_t\tilde{B}_t = p_t Y + e_t\tilde{H} + \tilde{r}_{t-1}e_t\tilde{D}_{t-1} + e_t y_t \tilde{B}_{t-1} + \int_0^1 \pi_{t-1}(i)di$$

where e_t is the exchange rate, Y is a consumption endowment, $\pi_{t-1}(i)$ represents the profit of intermediary i, and tildes denote U.S. values. The assumption that the U.S. owns the consumption endowment simplifies the model, and the prices of oil and the consumption good reflect the law-of-one price. As with the oil-exporting consumer, the U.S. consumer is subject to a deposit-in-advance constraint $p_t\tilde{C}_t + v_t\tilde{X}_t e_t r_{t-1} \leq \tilde{r}_{t-1}e_t\tilde{D}_{t-1}$.

We assume a fixed endowment of the non-tradable good, $H = \tilde{H} = \frac{1}{\gamma}$, which pins down each household's marginal utility of consumption. Our assumption of a deposit-in-advance constraint simplifies the problem, and with logarithmic utility, it leads to a fixed demand for deposits:

$$D_t = \bar{D} \qquad \tilde{D}_t = \tilde{D}$$

whenever r_t and $\mathrm{E}\left[e_{t+1}\right] e_t^{-1} r_t$ are less than β^{-1}. This assumption makes analyzing the effect of oil demand shocks less difficult. With deposit demand and the exchange rate fixed, the oil exporter's central bank must balance payments by buying or selling U.S. assets, consistent with standard economic intuition. But assuming that consumers' deposit demand is responsive to interest rates would not materially change the model's conclusions.

Meanwhile, the household's logarithmic utility combined with the deposit constraint implies that:

$$\begin{aligned} p_t C_t &= \frac{1}{(1+\omega_t)} r_{t-1}\bar{D} & \qquad v_t X_t &= \frac{\omega_t}{(1+\omega_t)} r_{t-1}\bar{D} \\ p_t\tilde{C}_t &= \frac{1}{(1+\omega_t)} e_t\tilde{r}_{t-1}\tilde{D} & \qquad v_t\tilde{X}_t &= \frac{\omega_t}{(1+\omega_t)} e_t\tilde{r}_{t-1}\tilde{D} \end{aligned}$$

which leads to a straightforward expression for net exports:

$$\mathrm{NX}_t(\omega) = \frac{\omega_t}{(1+\omega_t)} e_{t-1}\tilde{r}_{t-1}\tilde{D} + \left(1 - \frac{\omega_t}{(1+\omega_t)}\right) r_{t-1}\bar{D} \tag{12}$$

As ω_t increases, the U.S. consumer demands a higher share of oil in their consumption bundle, and the consumer in the oil-exporting country demands a lower share, leading to an increase in net exports. At the same time, the oil price rises as global demand increases. This lays out the basic mechanisms necessary for the rest of the model.

B Model Solution

In this appendix, we derive the implications discussed in the model section above.

B.1 Determination of y_t

First, we examine the determination of y_t. This price is pinned down by the total amount of Treasuries held by the U.S. household:

$$\begin{aligned} \tilde{B}_t &= \bar{B} - B_t^C - B_t \\ &= \bar{B} - Q_t - \mathrm{NX}_t + (r_{t-1} - 2)\bar{D} - \tilde{D} + \bar{A} \end{aligned}$$

this reflects the fixed deposit base of the intermediary and the size of the oil producing central bank's change in assets, but not the asset mix of the central banks. Intuitively, if the central bank sells more Treasuries and fewer deposits with the Fed, it leads to fewer purchases by the intermediary who now has to hold more reserves. While this decision determines liquidity premia, it does not affect the total amount of Treasuries going to U.S. households, so it leaves U.S. yields unaffected. Therefore it is not only independent of the decision on asset mix in period 2, it is also independent of whether or not the oil producing central bank is constrained.

B.2 Intermediaries' problem

We begin by analyzing the intermediaries' problem. The first order conditions require that:

$$r_t - \delta_t = c(1-\theta)\,\mathrm{E}\left[F(\theta D_t - M_t + S_t)\right] \tag{13}$$

$$\tilde{r}_t - \tilde{\delta}_t = c(1-\theta)\,\mathrm{E}\left[F(\theta \tilde{D}_t - \tilde{M}_t - e_t^{-1} S_t)\right] \tag{14}$$

These first-order conditions balance the difference between deposit rates and rates on excess reserves against the expected costs of receiving loans from the central bank. Meanwhile, Treasury yields must carry an extra premium because they cannot be sold to meet deposit outflows in the afternoon. Given the fixed deposit rate $\bar{\delta}$ and consumers' required rate of return, Equation (13) determines the domestic demand for reserves the central bank must meet. With the rate on foreign deposits $\bar{r}_F$ externally determined and the total supply of foreign reserves fixed, Equation (14) with the central banks' asset decisions determine the rate on foreign reserves $\tilde{\delta}_t$.

The first-order conditions also imply a deviation from uncovered interest parity:

$$\frac{1}{c\theta}\left(\mathrm{E}\left[\frac{e_{t+1}}{e_t}\tilde{r}_t\right] - r_t\right) = \mathrm{E}\left[\frac{e_{t+1}}{e_t}\right]\mathrm{E}\left[F(\theta\tilde{D}_t - \tilde{M}_t, s_t)\right] - \mathrm{E}\left[F(\theta D_t - M_t, s_t)\right] \tag{15}$$

The difference between the expected return on a U.S. deposit and an oil-exporting country's deposit responds to the differences in market liquidity between the exporter and the United States. For the same level of reserves, if the oil-exporting country's deposits increase and U.S. deposits decrease, the U.S. rate falls relative to the rate prevailing in the oil exporter. Similarly, if U.S. reserves increase and the oil exporter's reserves increase, U.S. interest rates fall relative to those of the oil exporter. These deviations persist whether the exchange rate is fixed or floating, and they rationalize the interest rate differentials we observe in the data.

A similar equation relates these quantities to monetary policy directly:

$$\frac{1}{c}\left(\mathrm{E}\left[\frac{e_{t+1}}{e_t}\tilde{\delta}_t\right] - \delta_t\right) = \mathrm{E}\left[\frac{e_{t+1}}{e_t}\right]\mathrm{E}\left[F(\theta\tilde{D}_t - \tilde{M}_t, s_t)\right] - \mathrm{E}\left[F(\theta D_t - M_t, s_t)\right] \tag{16}$$

Given the demand for deposits and the monetary policy decisions of the Federal Reserve and the oil exporter's central bank, this equation determines the exchange rate. In turn, the disconnect between the rates on reserves in the two countries determines the interest rate differential as:

$$\theta(\tilde{\delta}_t - \delta_t) = \tilde{r}_t - r_t$$

Thus the interest rate differential is proportional to the difference between policy rates in the two countries. In response to a shift in U.S. liquidity, the oil-exporting country's central bank must either change its supply of reserves or tolerate a shift in domestic interest rates to keep its exchange rate fixed.

In this setup, we see the model's primary mechanism. All else equal, a shift from the oil exporter's central bank Treasury holdings to reserves raises domestic deposit rates. Substituting the intermediary's budget constraint into (14), and taking account of the assumption of a fixed policy of the Federal Reserve and market clearing conditions for reserves and Treasuries, gives:

$$\tilde{r}_t - \bar{\delta} = c(1-\theta)\,\mathrm{E}\left[F\left(\theta(\bar{B} - B_t^C - \tilde{B}_t) - (1-\theta)(\bar{M} - \tilde{M}_t^C) + \theta e_t^{-1} M_t - \theta e_t^{-1} D_t - e_t^{-1} S_t\right)\right]$$

As the central bank's holdings of Treasuries decrease, more Treasuries must be held by the intermediary, meaning increased liquidity risk. Similarly, as the central bank's holdings of U.S. reserves increase, these reserves are denied to the intermediary, leading to increased liquidity risk in the afternoon.

B.3 Oil-producing central bank's problem

We assume for simplicity that the oil exporter fixes $\bar{e} = 1$, and begin by examining the central bank's problem in period 2.

In period 2, $\delta_2 - \tilde{\delta}_2$ is determined by the central banks' decisions over interest rate targets and the intermediary's desire to target the interest rate:

$$cF(\tilde{D} - \bar{A} + \tilde{M}_2^C) - cF(\bar{D} - M_2) = \delta_2 - \tilde{\delta}_2 = \frac{\chi\left(1 - G(\tilde{M}_2^C)\right) - cf(\theta\bar{D} - M_2)}{1 + \kappa cf(\theta\bar{D} - M_2)} M_2$$

where G is the cumulative distribution function of the aggregate shock, S_t,

Provided the oil producing central bank can sell Treasuries on the margin, the liquidity premium in the United States is determined by the fixed supply of U.S. reserves and precautionary demand of the intermediary for reserves and the desired level of reserve holdings by the foreign central bank:

$$cF(\tilde{D} - \bar{A} + \tilde{M}_2^C) = y_t - \tilde{\delta}_t = \chi\left(1 - Q(\tilde{M}_2^C)\right)$$

This fixes the equilibrium level of deposits held by the foreign central bank with the Fed, and importantly does not depend on the level of net exports or any other endogenous variable. In turn, once deposits with the Fed are determined, domestic supply is determined by the equation above. This fixes the level of reserves if the Treasury market is liquid at $M_2 = M_2^\star$ and $\tilde{M}_2^C = \tilde{M}_2^\star$, in turn fixing $d_2 - \tilde{d}_2$ and $y_2 - \tilde{d}_2$. Yields then vary according to net exports as described above. In contrast, if Treasuries are illiquid, then these spreads depend on net exports and net worth, reflecting the central bank'ss budget constraint.

In period 1, the oil producing central bank chooses reserves, deposits and Treasury holdings to maximize thier expected portfolio returns at the end of period 2. At the optimal level of deposits with the Fed:

$$\begin{aligned}\mathrm{E}\left[y_2\right] y_1 = \tilde{\delta}_1 p \Phi(X_2^\star)\,\mathrm{E}\left[\tilde{\delta}_2 + \psi\left(1 - G\left(\tilde{M}_2^C\right)\right)\middle|\mathrm{NX}_2 < X_2^\star\right] \\ + \tilde{\delta}_1 p (1 - \Phi(X_2^\star))\,\mathrm{E}\left[y_2 \middle| \mathrm{NX}_2 > X_2^\star\right] + \tilde{\delta}_1 (1-p)\,\mathrm{E}\left[y_2\right]\end{aligned}$$

where the left hand side reflects the expected return on Treasuries, and the right hand side reflects the expected return on deposits with the Fed. The right hand side has three components: if Treasuries are liquid tomorrow, the marginal return on a dollar of deposits is equal to the return on Treasuries. Similarly, if the central bank chooses not to sell Treasuries, the marginal return on a dollar of deposits is equal to the return on Treasuries. Otherwise, the marginal return will be below the return on Treasuries as the no-sale constraint will be binding. This will occur whenever:

$$\mathrm{NX}_2 < X_2^\star \equiv \tilde{M}_2^\star - M_2^\star + (r_{t-1} - 1)\bar{D} - \tilde{\delta}_1 \tilde{M}_1^C + \delta_1 M_1$$

or in other words when the central bank is unable to afford its optimal level of deposits and reserves without selling Treasuries, which it is unable to do when Tresuries are illiquid.

Rearranging the above yields the equilibrium condition for $\tilde{M}_1^C$:

$$\mathrm{E}\left[y_2\right] F(\theta\tilde{D} - \bar{A} + \tilde{M}_1^C) = p\Phi(X_2^\star)\,\mathrm{E}\left[\psi\left(1 - G\left(\tilde{M}_2^C\right)\right) - cF(\theta\tilde{D} - \bar{A} - \tilde{M}_2^C)\middle|\mathrm{NX}_2 < X_2^\star\right]$$

The left hand side is increasing in $\tilde{M}_1^C$, with a minimum of 0 and a maximum of $\mathrm{E}\left[y_2\right] c$. The right hand side is decreasing in $\tilde{M}_1^C$ (since it is increasing in $X_2^\star$), with a minimum of 0 and a maximum of $p\psi$. Equilibrium is determined by the intersection of these two lines, as shown in Figure 9. At this point, the return on U.S. liquidity for the intermediary is equal to the return on U.S. liquidity for the foreign central bank. This describes the demand curve for deposits with the Fed which we employ in our analysis above.

Figure 1: **Bid-ask spreads for off-the-run Treasuries ($).** March illiquidity was concentrated in off-the-run securities. Spreads are the difference between bid and ask prices for $100 notional in the fourth-from-most-recent Treasury issuance as of January 2020.

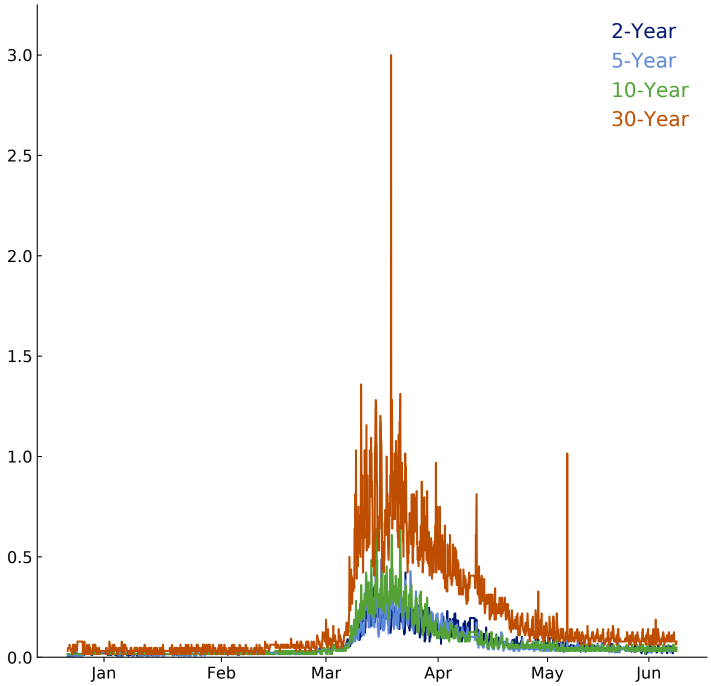


Figure 2: **Foreign official sales and dollar liquidity.** This figure shows foreign official Treasury holdings, swap lines, and investments into the foreign repo pool as reported in the Federal Reserve's Factors Affecting Reserves release. All values are differences from their values as of March 1st, 2020.

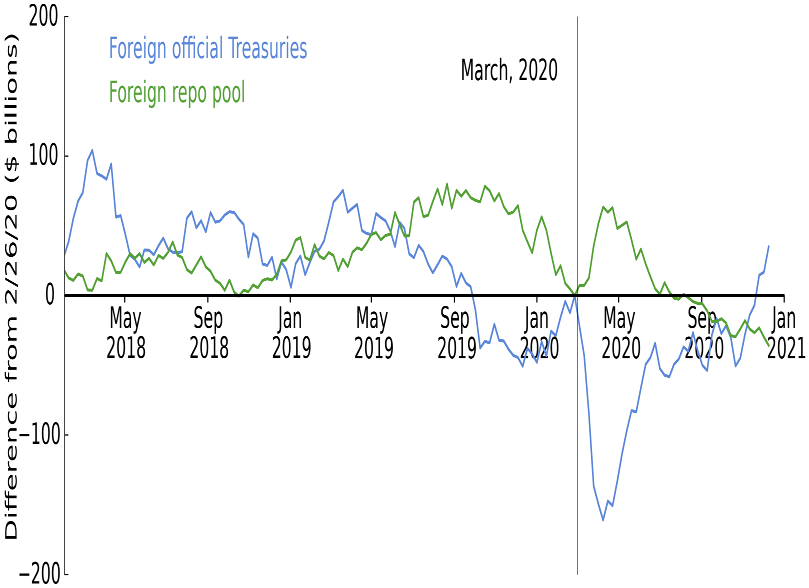
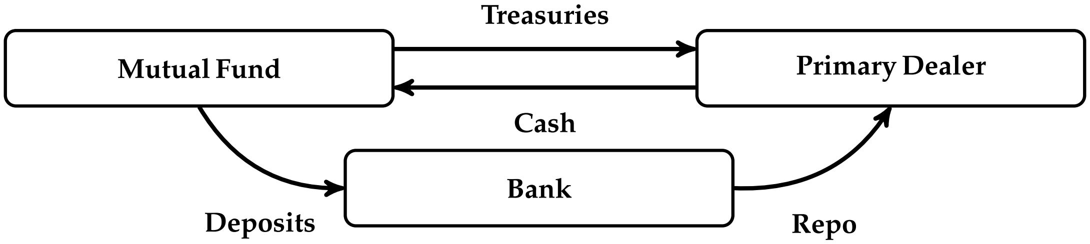


Figure 3: **Diagram depicting sales by domestic mutual funds and sales by foreign central banks.** Arrows denote the flow of cash or securities. The top panel examines the effects of sales by mutual funds. The bottom panel examines the effects of sales by foreign central banks which are invested in the foreign repo pool. In the top panel, funds from the sale are made available to the primary dealer through banks. In the bottom panel, funds enter the foreign repo pool and are therefore unavailable to the dealer.

Sales invested in a domestic bank



Sales invested in the foreign repo pool

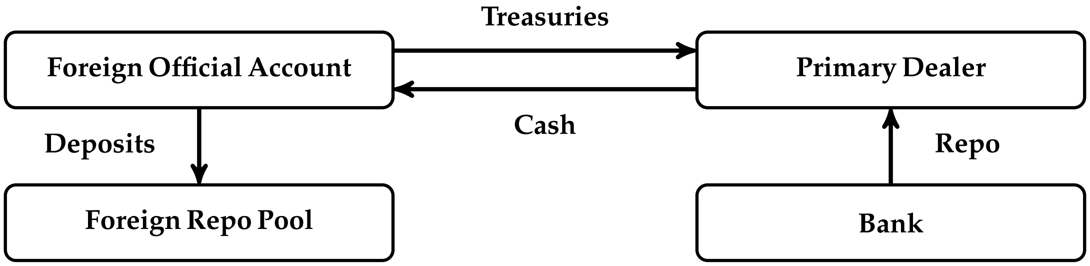


Figure 4: **Foreign official sales and repo rates during March.** Sales (in blue) are weekly changes in foreign custody holdings with the Federal Reserve Bank of New York. The SOFR-IOER spread (in green) is the spread on the SOFR index over the interest rate on excess reserves, a measuer of repo market illiquidity.

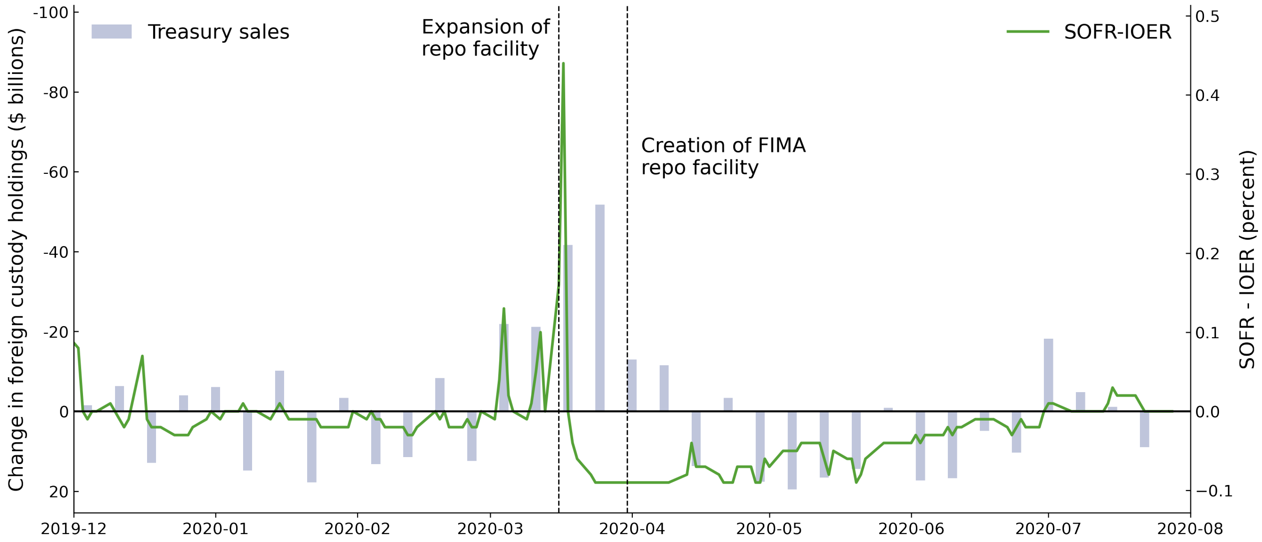


Figure 5: **Treasury sales in March 2020.** Sales are the difference between positions at the end of February and end of March for total Treasuries using the TIC major foreign holders of Treasuries data.

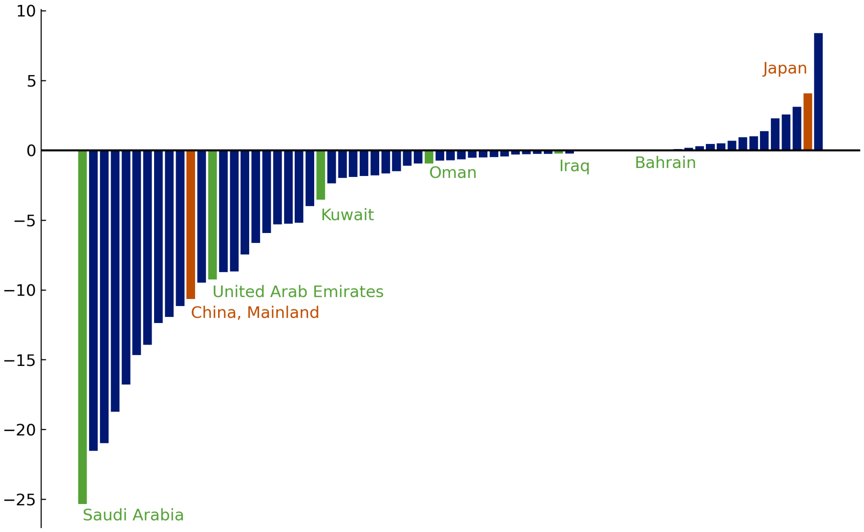


Figure 6: **Location of sample countries.** The five countries in the sample of major oil exporter TIC countries with pegged exchange rates are highlighted in green.

Figure 7: **Implied interest rate differentials across sample countries.** Daily implied differentials from forward and spot exchange rates

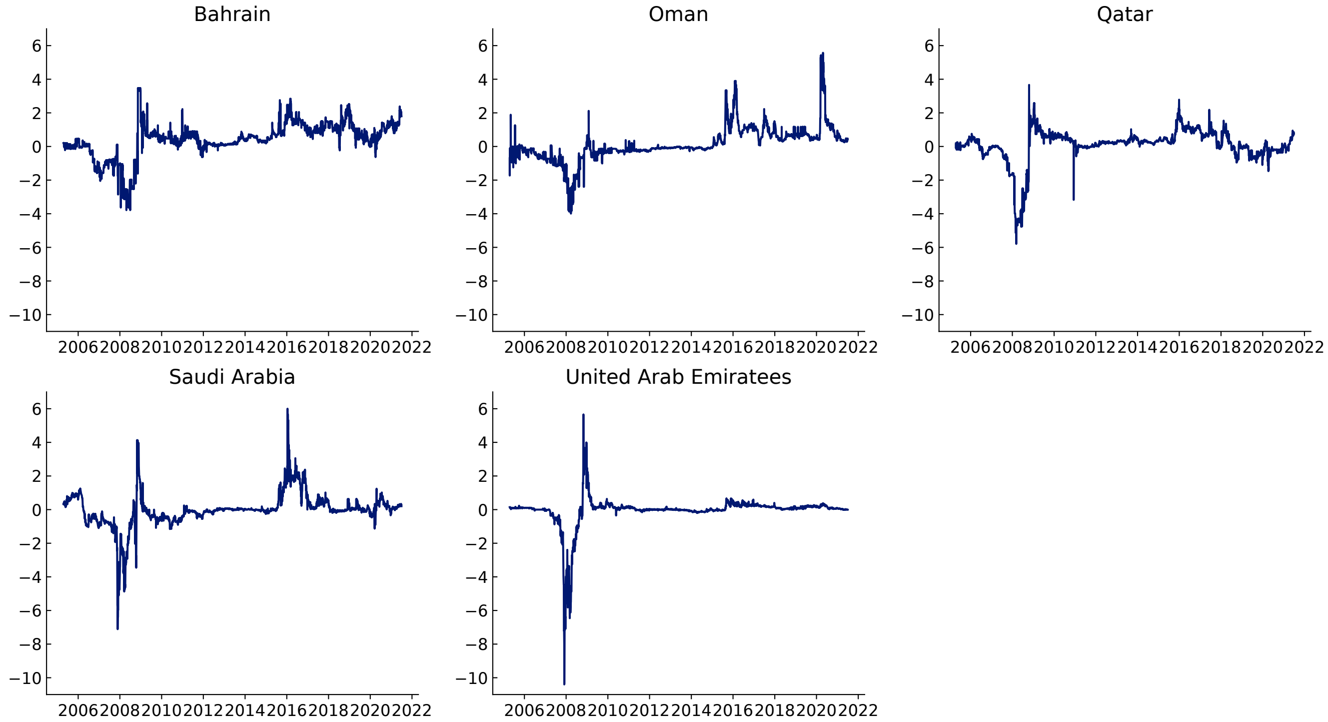


Figure 8: **Implied interest rate differentials, oil volatility and Treasury sales.** This figure shows daily data on Brent option-implied volatility from at-the-money options along with daily data on interest rate differentials implied by exchange rate spot and forward swap prices and month data on Treasury sales imputed from changes in TIC holdings of our five sample major oil exporters with exchange rates pegged to the U.S. dollar. All series have been standardized so that they are mean zero and variance one in the sample.

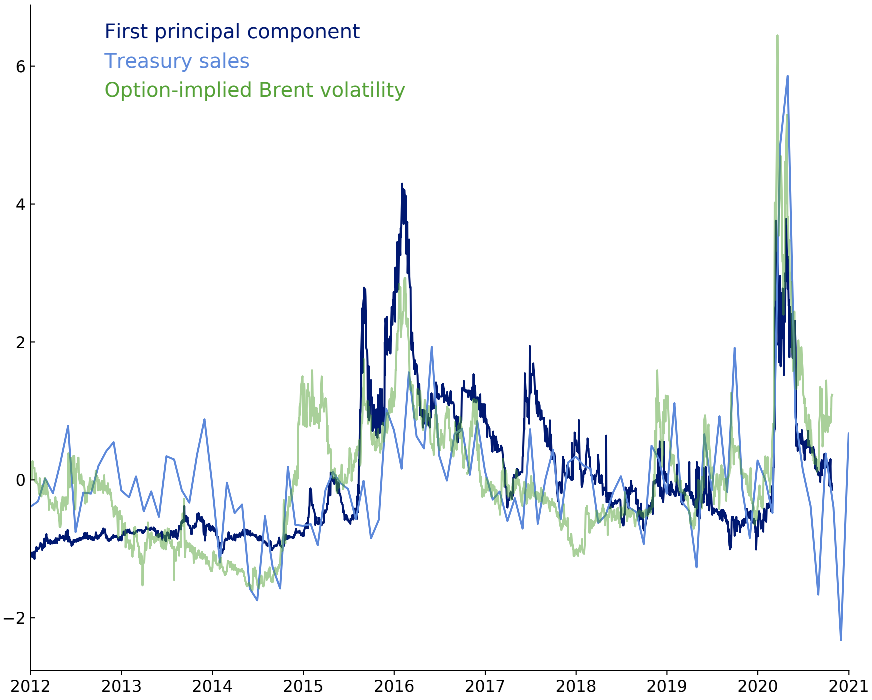


Figure 9: **Equilibrium in the model economy in period 1:** Equilibrium in the model occurs at the intersection of te red line, describing the return on U.S. liquidity for the foreign central bank, and the blue line describing the return on U.S. liquidity for the intermediaries. Darker red lines denote an increase in σ_X, the variance of the net exports shock.

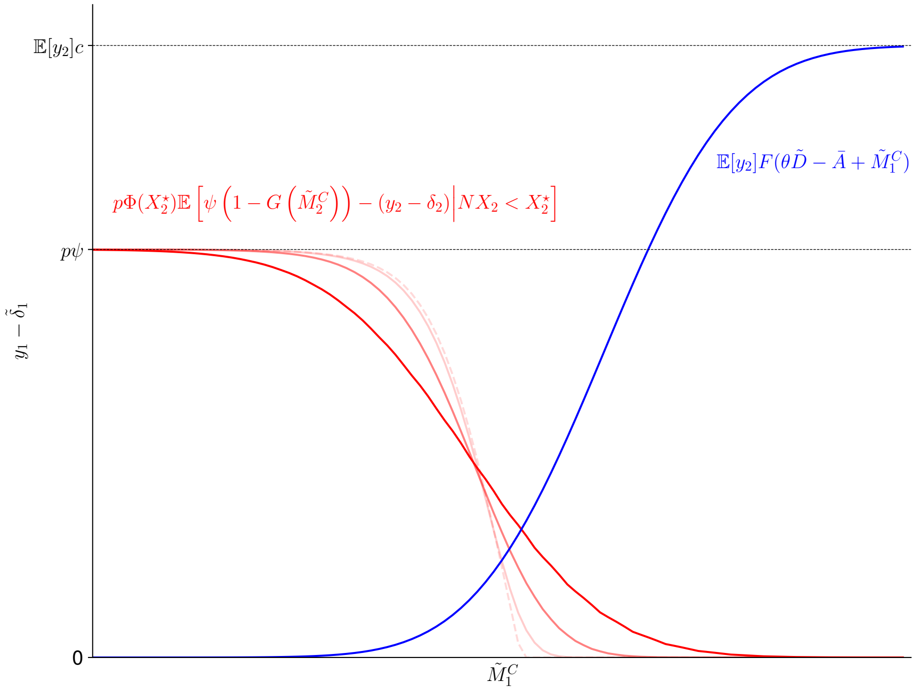


Figure 10: **Introduction of the FIMA repo facility in the model economy:** The preliminary equilibrium in the model occurs at the intersection of te red line, describing the return on U.S. liquidity for the foreign central bank, and the blue line describing the return on U.S. liquidity for the intermediaries. Darker red lines denote an increase in σ_X, the variance of the net exports shock. With the introduction of the FIMA repo facility, the cost of insufficient settlement balances is reduced, and equilibrium occurs at the intersection of the green and blue lines. Demand for deposits with the Fed decreases, and spreads fall. Moreover, increases in volatility of net exports lead to smaller increases in deposit demand and U.S. illiquidity.

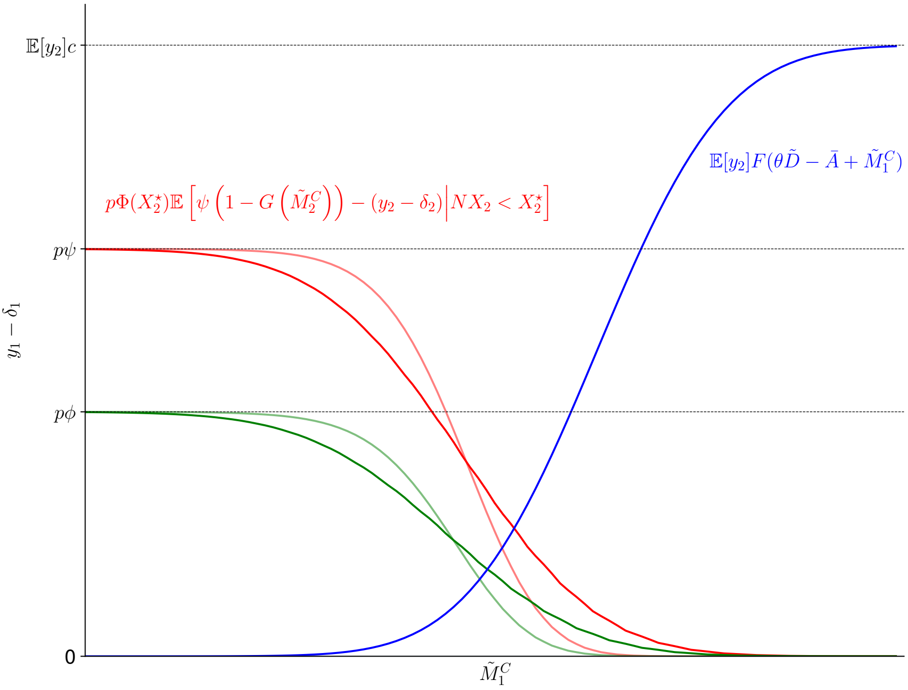


Figure 11: **Diagram of money markets and money market rate aggregates.** Arrows denote the flow of cash from cash lenders to cash borrowers. Dashed lines denote unsecured funding, while solid lines denote secured funding. For secured funding, securities flow in the opposite direction of the solid lines. Colored boxes denote the ranges of transaction each rate employed in this paper covers.

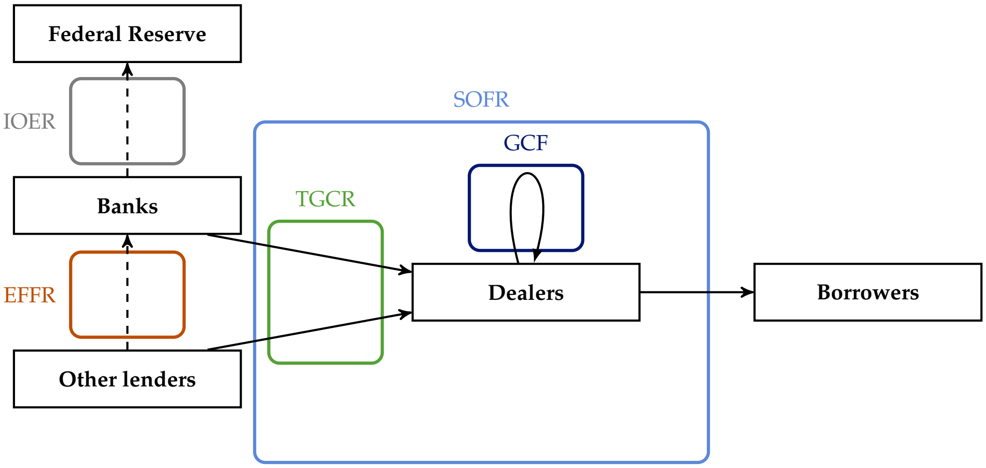


Table 1: **Total Treasury sales by group.** This table shows total sales, long-term Treasury sales and short-term Treasury sales by country groups from the TIC holdings table in March 2020. Amounts are in billions of dollars. High oil production countries are countries in the top third of the TIC sample for oil production per capita (after removing countries without oil production). Hedge-fund domiciles are Bermuda, British Virgin Islands, Cayman Islands, Ireland, and Luxembourg. East Asian countries are China, Hong-Kong, Macau, South Korea, Taiwan, Thailand, and Vietnam.

		Treasury sales	
	Total	Long-term	Short-term
High oil production	109.331	102.220	7.286
East Asia	34.699	50.244	-15.205
Hedge fund domeciles	46.956	59.977	-13.021
Foreign official accounts	147.052	124.194	22.858
All countries	260.719	251.780	8.939

Table 2: **Long-term Treasury sales in March 2020 by oil production per capita.** This table shows sales of long-term Treasuries from the TIC holdings table in March 2020. Amounts are in billions of dollars. The first column reports the number of countries, the second total sales of long-term Treasuries, the third average sales of long-term Treasuries. The fourth column reports controlled average sales, which are coefficients from a regression of total sales on GDP, a dummy for hedge-fund domiciles (Bermuda, British Virgin Islands, Cayman Islands, Ireland, and Luxembourg), and a dummy for East Asia countries (China, Hong-Kong, Macau, South Korea, Taiwan, Thailand, and Vietnam), and a dummy for the group they fall under for oil production per capita, where no oil production is excluded to avoid multicollinearity.

		Long-term Treasury sales			
Oil production per capita	**Countries**	Total sales	Average sales	Average sales (controlled)	t-stat
No oil production	22	80.024	3.637	-	-
Low	27	33.921	1.256	-0.160	-0.109
Middle	26	36.287	1.396	0.412	0.273
High	26	102.220	3.932	3.140	2.049

Table 3: **Countries in the Treasury International Capital System data with dollar pegs.** This table lists all countries in the TIC data that have dollar pegs as identified by the IMF's 2020 Annual Report on Exchange Arrangements and Exchange Restrictions. Countries classified as major oil exporters and countries with active futures markets are noted.

TIC countries with dollar peg	Oil exporters	Oil exporters with active futures market
Aruba		
The Bahamas		
Bahrain	✓	✓
Barbados		
Belize		
Curacao		
Iraq	✓	
Oman	✓	✓
Qatar	✓	✓
Saudi Arabia	✓	✓
United Arab Emirates	✓	✓

Table 4: **Summary statistics for the sample of oil countries with pegged exchange rates.** All quantities are normalized by GDP.

	Country				
	Bahrain	**Oman**	**Qatar**	**Saudi Arabia**	**UAE**
Exports	0.47	0.51	0.41	0.33	0.92
Imports	0.34	0.31	0.17	0.64	0.64
Net Exports	0.13	0.20	0.25	0.15	0.29
Government Debt	0.83	0.61	0.62	0.18	0.27
External Debt	≈ 2	0.94	1.38	0.23	0.82
Currency Reserves	0.10	0.22	0.21	0.63	0.25

Table 5: **Exchange rate peg and actual daily exchange rate distribution by country.** Data for the exchange rate distribution are from Refinitiv Eikon from November 1990 to October 2020.

		Empirical percentile						
	Peg	Min	0.10	0.25	0.50	0.75	0.90	Max
Bahrain	**0.377**	0.188	0.377	0.377	0.377	0.377	0.377	0.382
Oman	**0.384**	0.384	0.385	0.385	0.385	0.385	0.385	0.388
Qatar	**3.640**	3.614	3.640	3.640	3.641	3.641	3.642	3.864
Saudi Arabia	**3.750**	3.705	3.750	3.750	3.750	3.751	3.751	3.770
United Arab Emirates	**3.672**	3.656	3.673	3.673	3.673	3.673	3.673	3.704

Table 6: **Daily implied interest rate differential distribution by country.** Data for the exchange rates and forward exchange swap rates are from Refinitiv Eikon for April 2005 to July 2021. Interest rate differentials are annualized and reported in percentage points. The top panel includes all years while the bottom panel excludes 2007-2009 and Q1-Q2 of 2020.

	Empirical percentile (all years)						
	Min	0.10	0.25	0.50	0.75	0.90	Max
Bahrain	-1.273	-0.286	0.037	0.164	0.328	0.504	1.167
Oman	-3.721	-0.681	-0.260	-0.068	0.581	1.091	5.193
Qatar	-4.344	-0.464	-0.071	0.165	0.412	0.725	2.746
Saudi Arabia	-3.348	-0.373	-0.165	-0.011	0.107	0.421	2.826
United Arab Emirates	-7.101	-0.103	-0.011	0.044	0.120	0.191	3.866

	Empirical percentile (excluding crises)						
	Min	0.10	0.25	0.50	0.75	0.90	Max
Bahrain	-0.531	0.000	0.058	0.191	0.371	0.504	0.955
Oman	-1.611	-0.275	-0.156	-0.014	0.623	1.091	3.637
Qatar	-2.380	-0.218	-0.026	0.181	0.401	0.687	2.088
Saudi Arabia	-0.544	-0.219	-0.053	0.003	0.129	0.453	2.826
United Arab Emirates	-0.240	-0.038	-0.005	0.044	0.109	0.169	0.457

Table 7: **Correlation of implied interest rate differentials across countries.** Implied interest differentials are calculated on a daily basis from spot exchange rates and three-month forward swap agreements from 2005 to 2021. This table presents the correlations among these interest rate differentials for the five countries.

	Bahrain	**Oman**	**Qatar**	**Saudi Arabia**	**UAE**
Bahrain	1.00	0.65	0.69	0.65	0.56
Oman		1.00	0.50	0.62	0.47
Qatar			1.00	0.65	0.66
Saudi Arabia				1.00	0.73
UAE					1.00

Table 8: **Implied interest rate differentials and oil price volatility.** Implied interest differentials are calculated on a daily basis from spot exchange rates and three-month forward swap agreements from 2005 to 2021. Oil price volatility is calculated from at-the-money options on Brent futures. The first column presents the correlations between interest rate differentials and our factor based on the first principal component. The second column presents the correlation between interest rates and Brent oil volatility. The final two columns present the coefficient and standard error from regressions of each currency's implied interest rate differential (in basis points) on oil volatility from 2012 to 2021. All columns use daily data.

	Correlations		**Regression on oil volatility**	
	Principal component	Brent volatility	Coefficient	Standard error
Bahrain	0.800	0.212	0.451	(0.036)
Oman	0.864	0.305	5.730	(0.098)
Qatar	0.824	0.119	0.212	(0.077)
Saudi Arabia	0.839	0.265	1.299	(0.058)
UAE	0.791	0.259	0.513	(0.016)
Principal component	1.000	0.289	4.549	(0.096)

Table 9: **Summary statistics for repo rate spreads.** This table presents summary statistics for the various repo rate spread measures used in this paper from August 2014 to November 2020 on a daily basis.

	SOFR-IOER	GCF-IOER	GCF-TGCR	GCF-EFFR
Mean	-0.084	-0.014	0.101	0.054
Standard deviation	0.136	0.170	0.083	0.148
Minimum	-0.290	-0.302	-0.058	-0.212
25%	-0.170	-0.099	0.064	0.011
50%	-0.100	-0.012	0.087	0.049
75%	-0.010	0.046	0.124	0.087
Max	3.150	3.907	2.199	3.707

Table 10: **First stage of instrumental variables regressions for repo spreads.**

	Spread measure			
	SOFR - IOER	GCF - IOER	GCF - TGCR	GCF - EFFR
Oil price volatility	0.014*	0.032***	0.014*	0.032***
	(0.008)	(0.007)	(0.008)	(0.007)
Oil price volatility = L,	0.043***	0.025***	0.043***	0.025***
	(0.008)	(0.007)	(0.008)	(0.007)
Bill issuance	0.000	−0.000	0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Note issuance	−0.000	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)
FOMC	−0.039	−0.030	−0.039	−0.030
	(0.057)	(0.045)	(0.057)	(0.045)
Month-end dummy	0.045	0.048	0.045	0.048
	(0.100)	(0.077)	(0.100)	(0.077)
OPEC Announcement	0.998	1.268	0.997	1.268
	(1.593)	(1.612)	(1.594)	(1.612)
WTI margin	−0.001***	−0.000***	−0.001***	−0.000***
	(0.000)	(0.000)	(0.000)	(0.000)
VIX	−0.003	−0.030***	−0.003	−0.030***
	(0.003)	(0.002)	(0.003)	(0.002)
CDS Saudi Arabia	2.034***	0.972***	2.034***	0.972***
	(0.089)	(0.072)	(0.089)	(0.072)
Observations	1,377	2,485	1,376	2,485
R-squared	0.750	0.693	0.750	0.693

Table 10 summarizes the first stage of daily instrumental variables regressions of repo spreads on z-scores of our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 11: **Instrumental variables regressions for repo spreads.**

	Spread measure			
	SOFR - IOER	GCF - IOER	GCF - TGCR	GCF - EFFR
IR factor	2.545^{**}	5.295^{***}	3.675^{***}	2.708^{***}
	(1.028)	(0.758)	(0.564)	(0.651)
T-bill yield	0.114^{***}	0.118^{***}	0.005	0.042^{***}
	(0.007)	(0.005)	(0.004)	(0.005)
Bill issuance	0.003	0.004^{***}	0.002^{**}	0.004^{***}
	(0.002)	(0.001)	(0.001)	(0.001)
Note issuance	0.012^{*}	0.020^{***}	0.013^{***}	0.015^{***}
	(0.007)	(0.005)	(0.004)	(0.005)
FOMC	3.628^{***}	3.135^{***}	0.463	2.559^{***}
	(1.163)	(0.944)	(0.638)	(0.811)
Month-end dummy	4.560^{**}	2.780^{*}	2.551^{**}	6.850^{***}
	(2.064)	(1.626)	(1.132)	(1.396)
OPEC Announcement	-31.832	-126.001^{***}	-109.056^{***}	-104.459^{***}
	(32.836)	(34.059)	(18.016)	(29.237)
WTI margin	0.006^{***}	0.003^{***}	-0.000	0.002^{***}
	(0.001)	(0.000)	(0.000)	(0.000)
VIX	0.217^{***}	0.139^{***}	-0.081^{**}	0.033
	(0.068)	(0.045)	(0.037)	(0.038)
CDS Saudi Arabia	-4.905	-1.970	-1.255	2.351
	(3.296)	(2.005)	(1.809)	(1.721)
Observations	1,377	2,485	1,376	2,485
R-squared	0.380	0.275	0.157	0.131
IV F-stat	200.2	387.4	199.9	387.4

Table 11 summarizes the results of daily instrumental variables regressions of repo spreads (in basis points) on our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 12: **Uninstrumented regressions for repo spreads.**

	Spread measure			
	SOFR - IOER	GCF - IOER	GCF - TGCR	GCF - EFFR
IR factor	-1.956^{***}	-0.319	1.127^{***}	0.257
	(0.415)	(0.260)	(0.241)	(0.215)
T-bill yield	0.090^{***}	0.093^{***}	-0.008^{**}	0.032^{***}
	(0.007)	(0.006)	(0.003)	(0.006)
Bill issuance	0.003	0.004^{***}	0.002^{**}	0.004^{***}
	(0.002)	(0.001)	(0.001)	(0.001)
Note issuance	0.010^{*}	0.016^{***}	0.012^{**}	0.013^{***}
	(0.005)	(0.005)	(0.006)	(0.004)
FOMC	3.647	2.941	0.471	2.475
	(3.435)	(2.509)	(1.053)	(2.343)
Month-end dummy	4.493^{***}	2.842^{*}	2.507	6.875^{***}
	(1.480)	(1.487)	(1.808)	(1.509)
OPEC Announcement	-20.917	-110.911	-103.427^{*}	-98.955
	(29.973)	(76.314)	(57.025)	(60.178)
WTI margin	0.003^{***}	0.001^{**}	-0.002^{***}	0.001^{**}
	(0.001)	(0.000)	(0.000)	(0.000)
VIX	0.311^{***}	0.120^{**}	-0.027	0.025
	(0.082)	(0.054)	(0.057)	(0.041)
CDS Saudi Arabia	7.527^{***}	9.210^{***}	5.789^{***}	7.247^{***}
	(1.805)	(1.183)	(1.197)	(0.981)
Observations	1,385	2,493	1,384	2,493
R-squared	0.418	0.342	0.214	0.152

Table 12 summarizes the results of daily OLS regressions of repo spreads (in basis points) on our implied interest rate differential measure and a vector of controls. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 13: **Instrumental variables regressions for repo spreads, Jan 2010- Jan 2020.**

	Spread measure			
	SOFR - IOER	GCF - IOER	GCF - TGCR	GCF - EFFR
IR factor	2.297**	5.803***	3.608***	2.884***
	(1.002)	(0.881)	(0.555)	(0.751)
T-bill yield	0.104***	0.116***	0.002	0.039***
	(0.007)	(0.006)	(0.004)	(0.005)
Bill issuance	0.004**	0.005***	0.003***	0.004***
	(0.002)	(0.001)	(0.001)	(0.001)
Note issuance	0.011	0.021***	0.013***	0.015***
	(0.007)	(0.006)	(0.004)	(0.005)
FOMC	4.234***	3.441***	0.132	2.753***
	(1.194)	(0.984)	(0.661)	(0.840)
Month-end dummy	5.096**	3.121*	2.813**	7.088***
	(2.086)	(1.669)	(1.155)	(1.424)
OPEC Announcement	−64.801	−118.904**	−90.750***	−87.148**
	(48.625)	(50.394)	(26.922)	(42.978)
WTI margin	0.007***	0.004***	0.000	0.002***
	(0.001)	(0.000)	(0.000)	(0.000)
VIX	0.140	0.119**	−0.064	0.040
	(0.088)	(0.056)	(0.049)	(0.048)
CDS Saudi Arabia	−4.809	−2.764	−2.060	1.591
	(3.259)	(2.242)	(1.805)	(1.912)
Observations	1,296	2,404	1,295	2,404
R-squared	0.424	0.259	0.161	0.136
IV F-stat	216.9	306	216.5	306

Table 13 summarizes the results of daily instrumental variables regressions of repo spreads (in basis points) on our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls for the subsample from January 2010-January 2020 in columns 2 and 4 and from August 2014-January 2020 in columns 1 and 3. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 14: **Instrumental variables regressions for repo spreads, Jan 2015 – Jan 2020.**

	Spread measure			
	SOFR - IOER	GCF - IOER	GCF - TGCR	GCF - EFFR
IR factor	5.490***	6.823***	2.723***	5.487***
	(1.480)	(1.886)	(0.778)	(1.771)
T-bill yield	0.128***	0.130***	−0.004	0.060***
	(0.010)	(0.013)	(0.005)	(0.012)
Bill issuance	0.004**	0.007***	0.003***	0.007***
	(0.002)	(0.003)	(0.001)	(0.002)
Note issuance	0.012	0.020**	0.013***	0.019**
	(0.008)	(0.010)	(0.004)	(0.009)
FOMC	4.286***	4.715***	0.135	4.222***
	(1.316)	(1.674)	(0.691)	(1.573)
Month-end dummy	5.557**	6.812**	3.094***	12.235***
	(2.277)	(2.896)	(1.195)	(2.720)
OPEC Announcement	−75.771	−132.050**	−90.039***	−107.122*
	(52.392)	(66.644)	(27.501)	(62.596)
WTI margin	0.009***	0.009***	−0.000	0.006***
	(0.001)	(0.001)	(0.001)	(0.001)
VIX	−0.018	−0.060	−0.032	0.014
	(0.108)	(0.137)	(0.056)	(0.128)
CDS Saudi Arabia	−11.440***	−11.695**	0.150	−5.398
	(4.137)	(5.269)	(2.174)	(4.949)
Observations	1,210	1,209	1,209	1,209
R-squared	0.377	0.245	0.165	0.107
IV F-stat	119.6	119.1	119.1	119.1

Table 14 summarizes the results of daily instrumental variables regressions of repo spreads (in basis points) on our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls for the subsample from January 2015-January 2020. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 15: **Instrumental variables regressions for major holdings of Treasury securities.**

	Oil exporter holdings			**Foreign official holdings**		
	Total	Long-term	Short-term	Total	Long-term	Short-term
IR factor	−2.080	−2.246**	0.074	2.371	−7.204	9.575**
	(1.444)	(0.947)	(1.088)	(10.567)	(10.281)	(4.246)
T-bill yield	−0.016	−0.014**	−0.002	0.003	−0.009	0.012
	(0.010)	(0.007)	(0.008)	(0.067)	(0.065)	(0.027)
Bill issuance	−0.002	−0.001	−0.001	0.044***	0.034**	0.010*
	(0.002)	(0.001)	(0.001)	(0.014)	(0.013)	(0.006)
Note issuance	−0.003	−0.001	−0.001	0.024	0.019	0.005
	(0.003)	(0.002)	(0.002)	(0.024)	(0.024)	(0.010)
FOMC	1.162	0.853	0.197	11.634	10.762	0.872
	(1.725)	(1.132)	(1.300)	(13.840)	(13.465)	(5.560)
OPEC	−33.267	−30.677	−2.931	−603.742	−349.137	−254.605
	(62.407)	(40.941)	(47.019)	(422.498)	(411.063)	(169.744)
WTI margin	−0.002**	−0.001*	−0.001	−0.002	−0.008	0.006*
	(0.001)	(0.001)	(0.001)	(0.008)	(0.008)	(0.003)
VIX	−0.010	0.040	−0.068	3.203***	3.075***	0.128
	(0.136)	(0.090)	(0.103)	(0.918)	(0.893)	(0.369)
CDS Saudi Arabia	1.622	1.771	−0.149	−37.427	−0.801	−36.625**
	(4.855)	(3.185)	(3.658)	(42.192)	(41.050)	(16.951)
Observations	94	94	94	71	71	71
R-squared	0.64	0.73	0.21	0.56	0.56	0.26
IV F-stat	42.33	42.33	42.33	37.01	37.01	37.01

Table 15 summarizes the results of monthly instrumental variables regressions of month-on-month changes ($ billions) in foreign official holdings on our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 16: **Instrumental variables regressions for major holdings of Treasury securities, Jan 2010-Jan 2020**

	Oil exporter holdings			Foreign official holdings		
	Total	Long-term	Short-term	Total	Long-term	Short-term
IR factor	−3.842**	−3.283***	−0.656	−10.297	−15.026	4.730
	(1.692)	(1.100)	(1.240)	(12.354)	(12.747)	(4.774)
T-bill yield	−0.031**	−0.023**	−0.009	−0.054	−0.046	−0.008
	(0.014)	(0.009)	(0.010)	(0.087)	(0.090)	(0.034)
Bill issuance	−0.000	0.000	−0.000	0.045***	0.035**	0.009
	(0.002)	(0.001)	(0.002)	(0.017)	(0.018)	(0.007)
Note issuance	−0.002	−0.001	−0.001	0.031	0.022	0.009
	(0.003)	(0.002)	(0.002)	(0.023)	(0.024)	(0.009)
FOMC	2.080	0.950	1.025	12.112	10.325	1.786
	(1.852)	(1.204)	(1.358)	(13.766)	(14.203)	(5.320)
OPEC	−34.969	−52.749	13.427	−489.150	−351.147	−138.003
	(70.158)	(45.615)	(51.421)	(433.326)	(447.109)	(167.463)
WTI margin	−0.003***	−0.001*	−0.002**	−0.008	−0.011	0.003
	(0.001)	(0.001)	(0.001)	(0.008)	(0.009)	(0.003)
VIX	0.081	−0.065	0.132	1.511	1.578	−0.067
	(0.201)	(0.131)	(0.147)	(1.346)	(1.389)	(0.520)
CDS Saudi Arabia	4.913	4.062	0.817	11.383	31.209	−19.826
	(5.063)	(3.292)	(3.711)	(43.075)	(44.445)	(16.647)
Observations	90	90	90	67	67	67
R-squared	0.22	0.29	0.16	0.41	0.36	0.15
IV F-stat	32.27	32.27	32.27	23.46	23.46	23.46

Table 15 summarizes the results of monthly instrumental variables regressions of month-on-month changes ($ billions) in foreign official holdings on our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls for the subsample from January 2010-January 2020. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.

Table 17: **Instrumental variables regressions for primary dealer Treasury exposure and factors affecting reserves.**

	Difference from 90-day moving average			
	Dealer Treasuries	Custody holdings	Foreign repo	Swap lines
IR factor	3.254	−7.743*	5.177***	0.257
	(2.191)	(4.183)	(1.200)	(2.107)
T-bill yield	0.054***	−0.012	0.024***	−0.060***
	(0.016)	(0.030)	(0.009)	(0.015)
Bill issuance	−0.024***	0.058***	−0.002	0.067***
	(0.007)	(0.013)	(0.004)	(0.007)
Note issuance	−0.020***	0.012	0.004	−0.002
	(0.006)	(0.011)	(0.003)	(0.006)
FOMC	0.066	−0.125	1.386	0.201
	(2.066)	(3.946)	(1.132)	(1.988)
Month-end dummy	−4.062	−4.808	9.667***	2.820
	(4.316)	(8.243)	(2.365)	(4.152)
OPEC Announcement	−56.683	473.905*	−112.394	−401.859***
	(137.443)	(262.486)	(75.303)	(132.217)
WTI margin	0.000	−0.007***	0.003***	0.002
	(0.001)	(0.002)	(0.001)	(0.001)
VIX	0.970***	−0.459*	−0.046	−0.113
	(0.140)	(0.268)	(0.077)	(0.135)
CDS Saudi Arabia	−6.869	14.557	3.699	5.952
	(5.911)	(11.289)	(3.239)	(5.686)
Observations	521	521	521	521
R-squared	0.212	0.264	0.320	0.776
IV F-stat	90.38	90.38	90.38	90.38

Table 17 summarizes the results of weekly instrumental variables regressions of weekly primary deadler Treasury exposure and factors affecting federal reserve balances, expressed as weekly deviations from the 90-day moving average ($ billions) on our implied interest rate differential measure (instrumented for by oil option-implied volatility and OPEC announcements) and a vector of controls. Standard errors are shown in parentheses. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. Additional controls ommitted for readability are bond issuance, Treasury general account balances, corporate income tax payments, SOMA purchases and sales, the CESI index and Brent returns.