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# Foreign Reserve Management and U.S. Money Market Liquidity: A Cost of Exorbitant Privilege

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# Foreign Reserve Management and U.S. Money Market Liquidity: A Cost of Exorbitant Privilege *

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**Abstract**

We show theoretically and empirically that the dollar's status as the global reserve currency can lead to economically significant changes in U.S. money market liquidity. We develop a model in which U.S. money market spreads respond to foreign central banks' exchange-rate management decisions. 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. Our analysis focuses on the major oil exporting countries with fixed exchange rates because their foreign-exchange market interventions are straightforward to characterize. Our regression analysis shows that shifts in the central banks' demand for dollar liquidity related to oil price volatility are associated with significantly higher overnight 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, on average, to three billion dollars of Treasury sales and a two to six basis point increase in U.S. money market spreads. At the same time, deposits held with the Federal Reserve increase in response to this higher oil-price volatility, which is consistent with the model's predictions. This evidence indicates that the widespread use of the U.S. dollar as a reserve currency acts as a channel that can propagate funding shocks from the rest of the world to the United States.

**Keywords:** Treasury market, repurchase agreements, market liquidity, exorbitant privilege, exchange rate peg.
**JEL Codes:** E43, G12, G13, G23

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# 1 Introduction

The U.S. Treasury market is the deepest and most liquid market in the world and lies at the center of the U.S. and global financial systems. In recent years, however, several episodes of significant deterioration in Treasury market liquidity have led to dysfunction in some market segments. Those episodes have occurred in both stressed and benign market environments, raising questions about the economic forces contributing to the market's illiquidity and disruptions in market functioning. In this paper, we focus on one source of demand for dollar liquidity and how it contributes to fluctuations in U.S. money market liquidity – foreign central bank demand for dollars.

Policymakers and researchers commonly point to the events in September 2019 and March 2020 as examples of how Treasury market illiquidity can be disruptive to the broader financial system.[1] In September 2019, a surge in Treasury sales by foreign official accounts preceded the 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. For example, 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. These sales 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 because of their role as market makers in the Treasury market. The indirect effect relates to the reduced available reserves dealers could use to fund the purchases.

Foreign official institutions sold such an out-sized amount 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 meaning of the term has varied somewhat since the French finance minister Valéry Giscard d'Estaing coined it in the 1960s, we take it to mean the United States' unique ability to invest in equity and direct investment abroad while supplying liquidity to the rest of the world in the form of U.S. dollars (Gourinchas and Rey, 2007). As a result, the dollar makes up about 60%

[1] These two examples share common features with a similar stress episode in 1958. See Kahn and Nguyen (2022).

of global foreign exchange reserves.

September 2019 and March 2020 highlight the spillover effects of foreign reserve management on U.S. money markets and demonstrate how shocks to foreign dollar liquidity can propagate shocks to short-term funding markets in the United States. They are, however, stark examples of how the Treasury market's structure can be vulnerable to specific shocks. For instance, in 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. Moreover, although we have estimates of the size of the sales and directly observe that they correlate with reductions in U.S. money market liquidity, what is missing is a credible estimate of the size of the effect of foreign central bank sales on Treasury market liquidity.

To fill this gap, we draw motivation from these episodes and develop a model to understand foreign central banks' incentives to transact in Treasuries. We then use the model's predictions as a basis for the regression analysis and to identify the effect of shifts in foreign central bank Treasury demand on U.S. money market liquidity over a sample period from 2009 to 2020. In this way, we provide credible estimates of the size of the effect on U.S. liquidity related to the dollar's status as the global reserve currency. We focus specifically on Treasury sales by central banks in oil-exporting countries that peg their currencies to the dollar. This approach confers two advantages. First, oil-exporting countries account for a substantial share of total official holdings of Treasuries. Second, oil exporters with fixed exchange rates exhibit a predictable and readily characterized relationship between oil-price fluctuations, exchange rate changes, and Treasury holdings.

In this way, our paper builds on 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), Bahaj and Reis (2021), and Ferrara et al. (2022). The main predictions of our model are qualitatively similar to those in Bahaj and Reis (2021), who show that swap lines can achieve the same outcome with global banks and integrated financial markets, but domestic central banks, an international lender of last resort. In our model, introducing such a facility – say, in the form of the Foreign and

International Monetary Authorities (FIMA) Repo Facility – would augment dollar liquidity, unambiguously mitigating the effects of foreign central bank dollar demand on U.S. money market liquidity.

Our paper is also related to work that examines the relation between foreign Treasury holdings and Treasury prices (Bernanke et al., 2004; Warnock and Warnock, 2009; Bertaut et al., 2012; and Wolcott, 2020). These papers are primarily concerned with foreign holdings' impact on Treasury yields. For example, Warnock and Warnock (2009) and Wolcott (2020) find that larger Treasury demand holdings by foreign investors are associated with lower yields. By contrast, our paper focuses on the impact of foreign sales on U.S. domestic liquidity when foreign central banks demand liquidity by selling their Treasury holdings. We, therefore, turn the usual question about the effects of dollar illiquidity on emerging-market economies (EME) on its head. Instead of asking how market stress affects demand for dollar liquidity in EMEs, we ask how foreign exchange reserve management policies can amplify funding illiquidity in U.S. money markets.

To illustrate how foreign countries' exchange rate management can impair U.S. domestic liquidity, we model a small open economy that manages its exchange rate using both Treasuries and more liquid reserves. The model 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). Of these papers, our model is closest to Bianchi et al. (2021). Unlike that paper, we focus on the portfolio problem the foreign central bank faces in response to a terms-of-trade shock. The financial frictions in our model arise from intra-day management of reserves, similar Poole (1968), d'Avernas and Vandeweyer (2020), and Bianchi and Bigio (2022). This premise relates to our focus on the effects of terms-of-trade shocks on dollar liquidity in the small open economy, differentiating our paper from others that focus on exchange rates and financial frictions. When the central bank faces a terms-of-trade shock, it sells Treasuries but simultaneously demands dollar liquidity to provide buffers to domestic banks. This mechanism can lead to sharp rises in dollar rates as dollar liquidity decreases.

Guided by the model's predictions, we use oil-price volatility as an instrument to identify the effect of oil exporters' U.S. Treasury sales to manage their exchange rates. Our regression evidence indicates 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.

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 two versions of the model – one without an exchange rate peg, the other with – in sections 4 and 5. We then discuss the model's dynamics and calibration in sections 6 and 7. In section 8, we report the results of our empirical analysis, and in section 9, we look at the effects of foreign official sales on Treasury market functioning. Section 10 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.[2] 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. Foreign central banks likely

[2]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.

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. Crucially, sales of Treasuries 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 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 this 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 likely mitigated the effect of the foreign repo pool on the availability of funding, at the margin, the pool can nevertheless adversely affect Treasury liquidity by making repo balances more expensive.

During March 2020, the most significant sales did not come from the two largest holders of Treasuries, China and Japan, but from Saudi Arabia. Figure 4 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, these oil exporters' central banks and other official accounts likely dominated the amount of Treasuries sold during 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 our 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 try to adjust our average sales figures for some of these other motivations. 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. First, following Vissing-Jorgensen (2021), we control for countries that are hedge-fund domiciles (Bermuda, British Virgin Islands, Cayman Islands, Ireland, and Luxembourg). Hedge funds sold large amounts of Treasuries in March 2020, and many of those hedge funds were domiciled in those countries.[3] 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. Second, following Weiss (2022), we 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. Finally, we control for gross domestic product to capture the differences due to the scale of different 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.

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

## 3 Stylized facts on reserve management by oil exporters

In this section, we investigate the relationship 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. For our 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 5 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

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

countries then form a sensible group for comparison.

### 3.1 Exchange rate management

Although all five countries in our 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. During 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:

$$x_{i,t,m} \equiv \frac{F_{i,t,m}}{e_{i,t}} - 1 \quad (1)$$

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 2007-2009 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 6, we present the time series of these differentials normalized by their standard deviation. Several commonalities are evident. First, all series had large deviations during and immediately following the 2007-2009 financial crisis. Second, 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. This first component explains 69% of the daily variance in deviations and is insensitive to excluding episodes such as the financial crisis.

Crucially, there are two interpretations of what these implied interest rate differentials could 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 take the former interpretation and show how these interest rate differentials can be 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 where 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 relationship 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 our sample, we also use oil option implied volatility for Brent crude oil, derived from at-the-money options.

First, we examine the relationship 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 relationship with the first principal component. First, 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 relationship between the two series in a regression.

In Figure 7, we examine the relationship 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 during 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 this first principal component and Treasury sales is 52%. These figures suggest a strong statistical relationship among the three series.

The figure suggests a consistent relationship between oil price volatility, forward exchange deviations, and Treasury sales. However, we need to build a structural framework to interpret this relationship 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 reserve management and domestic liquidity

We consider a two-country model of an oil producer and the United States, each of which have a representative household and a central bank. Financial intermediation between the two countries is conducted by a continuum of international banks. The domestic household owns oil wells which produce oil that is demanded by both oil producer and United States consumers. The international banks take in domestic deposits and foreign deposits and uses them to purchase domestic and foreign reserves and to invest in foreign bonds. In deciding between reserves and Treasuries, banks face both domestic and foreign deposit requirements, which lead to liquidity premia that are reflected in the returns on reserves. Profits of the bankers are passed to the oil producer household which (for simplicity) owns all banks. The consumption good is produced by the U.S. economy. The price of oil is determined by a fixed number of wells and the demand of consumers which is subject to taste shocks which determine net exports.

## 4.1 Households

Oil producer households receive utility from consumption, $C_t$, oil, $X_t$, and non-tradable goods $N_t$. They have an endowment of oil wells, $W$, which produces a quantity of oil $W$ each period that sells at a globally determined price $v_t$, and an endowment of non-tradable goods, $H$. As we discuss below, the assumption of a constant supply of oil matches the high-frequency nature of our empirical work, since oil supply is likely to be fixed in the short-run. Consumers discount at a rate $\beta$ and maximize the discounted present value of their utility:

$$\sum_{t=0}^{\infty} \beta^t \, \mathrm{E} \left[ \frac{1}{1+\omega_t} \log(C_t) + \frac{\omega_t}{1+\omega_t} \log(X_t) + \gamma \log(N_t) \right] \tag{2}$$

where $\omega_t$ represents shock to oil demand which we assume are exogenous and which we use to generate changes in oil prices and the current account. This maximization is subject to the budget constraint:

$$p_t C_t + v_t X_t + D_t + \tau_t + N_t = v_t W + H + r_{t-1} D_{t-1} \tag{3}$$

where $p_t$ is the price of consumption, $v_t$ is the globally determined price of oil, $D_t$ are domestic deposits, 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 follows and simplifies deposit demand, allowing us easily to obtain equilibrium in financial markets. We discuss relaxing this assumption below.

The U.S. household is nearly symmetric in terms of preferences except they also have a demand for Treasuries:

$$\sum_{t=0}^{\infty} \beta^t \operatorname{E}\left[\frac{1}{1+\omega_t}\log(\tilde{C}_t) + \frac{\omega_t}{1+\omega_t}\log(\tilde{X}_t) + \gamma\log(\tilde{N}_t) + \rho\log(B_t)\right] \tag{4}$$

the U.S. household is subject to the same preference shock of oil, $\omega_t$. We can think of the demand for Treasuries the U.S. consumer has as representing a dimension of liquidity not captured below when we turn to intermediaries or as a reduced form of preferred habitat demand. The U.S. household also faces a different budget constraint represented in terms of the oil produceer currency:

$$p_t\tilde{C}_t + v_t\tilde{X}_t + e_t\tilde{D}_t + \tilde{\tau}_t + e_t\tilde{N}_t + e_t\tilde{B}_t = p_t Y + e_t\tilde{H} + \tilde{r}_{t-1}e_t\tilde{D}_{t-1} + e_t y_t\tilde{B}_{t-1} + \int_i \pi_{i,t-1}$$

where $e_t$ is the exchange rate, $Y$ is a consumption endowment, $\pi_{t-1}$ represents the profits of intermediaries, and tildes denote U.S. values. The assumption that the U.S. owns the consumption endowment is for simplifying purposes, and the prices of oil and consumption reflect the law-of-one price. As with the oil producing consumer, the U.S. consumer is subject to a deposit-in-advance constraint $p_t\tilde{C}_t + v_t\tilde{X}_t e_t r_{t-1} \leq \tilde{r}_{t-1}e_t\tilde{D}_{t-1}$.

### 4.2 International banks

There are a continuum of international banks. Each bank has a U.S. headquarters and an oil-producing country subsidiary, over which decisions are made jointly. The banks are open in the morning and the evening. In the morning, the oil-producing 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 producer reserves, $M_t$, U.S. reserves, $\tilde{M}_t$ or to holdings of U.S. Treasuries, $B_t$.

Similar to Poole (1968), d'Avernas and Vandeweyer (2020), Bianchi and Bigio (2022), and Bianchi et al. (2021) intermediaries in our model face an intra-day liquidity problem. In the evening, banks are exposed to two shocks. The first comprises idiosyncratic, mean zero deposit shocks $Z_t$ and $\tilde{Z}_t$, which reallocates deposits across banks within a country. The second is an aggregate, mean zero exchange shock $S_t$ which reallocates deposits between dollars and the oil producer currency. During the evening, exchange markets are shut down for banks and Treasuries cannot be converted to reserves. In the domestic and foreign markets, however, banks are subject to a reserve requirement:

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

If, in the afternoon, this requirement isn't 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' choice of deposits and reserves in the morning is then:

$$\mathrm{E}\left[L_t\right] = \mathrm{E}\left[L(\theta D_t - M_t + S_t)\right] = \mathrm{E}\left[\int_{-\infty}^{\theta D_t - M_t + S_t} (\theta D_t - M_t + S_t - Z) f(Z)\; dZ\right] \tag{5}$$

where $f$ is the probability density function for the deposit shocks, which has a cumulative distribution function $F$. This distribution depends on the variable $s$, for which higher levels represents a mean-preserving increase in the variance of the shock to deposit shocks. When $s$ is higher, this means that more banks than average must depend on the Federal Reserve's deposit facilities. We assume this shock is independent of change in oil prices and across countries and identically distributed over time.

The bank balances the cost of these loans against the returns on the various assets it holds. They are risk-neutral and live for only one period. This leads to the objective function:

$$\mathrm{E}\left[\pi_{t+1}\right] = \max_{B_t, D_t, \tilde{D}_t, M_t, \tilde{M}_t} \mathrm{E}\left[e_{t+1} y_t\right] B_t + \mathrm{E}\left[e_{t+1}\tilde{\delta}_t\right] \tilde{M}_t + \delta_t M_t - \mathrm{E}\left[e_{t+1}\tilde{r}_t\right] \tilde{D}_t - r_t D_t \qquad (6)$$

$$- c\,\mathrm{E}\left[L_t\right] - \mathrm{E}\left[c e_{t+1}\right] \mathrm{E}\left[\tilde{L}_t\right]$$

$$\text{such that: } \; e_t B_t + e_t \tilde{M}_t + M_t = e_t \tilde{D}_t + D_t \qquad (7)$$

where $r_t$ is the return on domestic deposits, $\delta_t$ is the return on domestic reserves, $\tilde{r}_t$ is the return on foreign (dollar) deposits, $\tilde{\delta}_t$ is the return on foreign reserves, and $Y$ is the return on foreign Treasuries. The constraint in this problem is the morning budget constraint for banks, which reflects their issuance of foreign and domestic deposits, and purchases of foreign and domestic reserves as well as Treasuries.

### 4.3 Oil-exporter's central bank

Our goal is to relate this situation to the asset holdings of the oil-producing country's central bank. Building on our motivating evidence above, we assume the central bank has access to two assets: U.S. Treasuries which it holds in quantity $B_t^C$ and deposits with the Federal Reserve which it holds in quantity $\tilde{M}_t^C$. These assets are used to back domestic reserves.

As with international banks, the domestic central bank faces an intra-day liquidity problem. It must meet the demand for international banks for domestic loans during 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, central banks cannot sell Treasuries but must instead sell reserves or rely on their holdings of deposits with the Federal Reserve. If these holdings are exhausted, as with the international banks, the foreign central bank faces a cost $\psi$ above the rate on U.S. reserves. This cost can be thought of as a penalty rate for an emergency loan from the Federal Reserve or other banks, or as a cost for selling other assets to raise dollars.

This setup implies a budget constraint for the central bank in the morning:

$$e_t B_t^C + e_t \tilde{M}_t^C = \tau_t + M_t + Q_t^C \tag{8}$$

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

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

which reflects the realization of the exchange shock $S_{t-1}$ as well as the profits on the central bank's other investments in the United States and the cost of borrowing in reserves.

We assume that the central bank acts to keep the exchange rate fixed, $e_t = \bar{e}$, and has a deposit target $\bar{\delta}$. We model deviations from this target as coming with a quadratic cost $\kappa^\star(\delta_t - \delta^\star)^2$, which can be thought of as resulting from inflation and employment trade-offs outside the confines of this model. To set the supply of reserves we assume the central bank minimizes:

$$\min_{M_t, \delta_t} M_t^2 + \kappa^\star \left(\delta_t - \delta^\star\right)^2 \tag{9}$$

subject to the demand for these reserves from international banks. To set the holdings of reserves, we assume that the central bank sets:

$$y_t - \tilde{\delta}_t = \psi[1 - G(e_{t-1} \tilde{M}_{t-1}^C)]$$

where $G$ is the cumulative distribution function for the exchange shock, $S_t$. This equation sets the marginal return on a dollar invested in foreign reserves equal to the households' discount factor.

### 4.4 Federal Reserve

For simplicity, we hold the policy of the Federal Reserve fixed. In particular, we assume that the Federal Reserve has a fixed balance sheet $\bar{A}$ that must back both foreign reserve holdings by international banks and the holdings of the oil-producing central bank. Therefore:

$$\bar{A} = \tilde{M}_t + M_t^C \tag{10}$$

This implies that the central bank does not respond to shocks which lead to sales by the foreign central bank. In practice, this is likely to be true in the short-term which is the concern of our model, though in the medium or long-term reserves are more likely to be adjusted.

Similarly, we assume that there is an externally determined supply of foreign Treasuries, $\bar{T}$, so that Treasuries must be held by either the domestic central bank, by international banks, or by U.S. households:

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

One objection to this assumption (as to the previous assumption) might be that the U.S. market is large relative to the demands placed by the oil producing countries which provide our setting. We have two responses to this objection. First, our results should persist in sign if not in magnitude even if we allow for elasticity in the supply of and demand for Treasuries so long as this elasticity is not *perfectly* elastic. Second, as we show in our empirical results below, sales of Treasuries by the foreign central banks we model do appear to affect domestic deposit rates, and as the results in March 2020 show, they can be materially large with respect to liquidity provided by the U.S. market.

### 4.5 Equilibrium

For an equilibrium, we need to clear seven markets: the market for oil, the market for the consumption good, the market for oil-producing currency deposits, the market for oil-producing currency reserves, the market for U.S. reserves, the market for U.S deposits, and the market for Treasuries. The paths for each variable are determined by the taste shock $\omega_t$, which we assume is an independent and identically distributed random variable. In this section, we will show that in response to a decrease in $\omega_t$, the central bank sells Treasuries, leading to an increase in interest-rate differentials and an increase in U.S. money market spreads as liquidity is drained from the U.S. market.

We begin by analyzing the interemdiaries' problem. First order conditions require:

$$r_t - \delta_t = c(1-\theta)\,\mathrm{E}\left[F(\theta D_t - M_t + S_t)\right] \tag{11}$$

$$\tilde{r}_t - \tilde{\delta}_t = c(1-\theta)\,\mathrm{E}\left[F(\theta \tilde{D}_t - \tilde{M}_t - e_t^{-1} S_t)\right] \tag{12}$$

These first order conditions balance the difference between deposit rates and rates on excess reserves against expected costs of receiving loans from the central bank. Meanwhile, Treasury yields must carry an extra premium from the fact that they cannot be sold to meet deposit outflows in the afternoon. Given the fixed deposit rate $\bar{\delta}$ and the required rate of return by consumers, Equation (11) determines the domestic demand for reserves the central bank must meet. Meanwhile, given the externally determined rate on foreign deposits $\bar{r}_F$ and the fixed total supply of foreign reserves, Equation (12) in combination 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, as:

$$\frac{1}{c\theta}\left(\mathrm{E}\left[\frac{e_{t+1}}{e_t}\tilde{r}_t\right] - r_t\right) = \mathrm{E}\left[\frac{e_{t+1}}{e_t}\right]\mathrm{E}\left[F(\theta\tilde{D}_t - \tilde{M}_t, s_t)\right] - \mathrm{E}\left[F(\theta D_t - M_t, s_t)\right] \tag{13}$$

which says that the difference between between the expected return on a U.S. deposit and an oil-producing deposit responds to the relative liquidity in U.S. and oil-producing country markets. For the same level of reserves, if oil-producing country deposits increase and U.S. deposits decrease, U.S. rates will fall relative to oil-producing rates. Similarly, if U.S. reserves increase and oil-producing country reserves increase, U.S. rates will again fall relative to oil producing rates. These deviations will persist regardless of whether or not the exchange rate is fixed, and therefore underpin our consideration of interest rate differentials in our motivation.

A similar equation relates these quantities to monetary policy directly:

$$\frac{1}{c}\left(\mathrm{E}\left[\frac{e_{t+1}}{e_t}\tilde{\delta}_t\right] - \delta_t\right) = \mathrm{E}\left[\frac{e_{t+1}}{e_t}\right]\mathrm{E}\left[F(\theta\tilde{D}_t - \tilde{M}_t, s_t)\right] - \mathrm{E}\left[F(\theta D_t - M_t, s_t)\right] \tag{14}$$

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:

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

or in other words, the interest rate differential is proportional to the difference between policy rates in the two countries. All else equal, in response to a shift in U.S. liquidity, in order to keep exchange rates fixed the oil producing country central bank must either change its supply of reserves or tolerate a shift in domestic interest rates.

Within this setup, we can start to see the main mechanism of the model. All else equal, a shift from oil-producing central bank Treasury holdings to reserves leads to an increase in domestic deposit rates. Substituting in the budget constraint of the intermediary into (12), 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 central bank's holdings of U.S. reserves increase, these reserves are denied to the intermediary, again leading to increased liquidity risk in the afternoon.

This result holds all else fixed, however, so we examine the demand for and supply of deposits. We assume a fixed endowment of the non-tradable good, $H = \tilde{H} = \frac{1}{\gamma}$ which pins down each households marginal utility of consumption. Our assumption of a deposit-in-advance constraint makes this problem simple, since with logarithmic utility this 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 $\beta^{-1}$. This substantially decreases the difficulty of analyzing the effect of shocks to oil demand. With deposit demand and the exchange rate fixed, the oil-producing country's central bank must balance payments by buying or selling U.S. assets, matching conventional wisdom. But the consumers' deposit demand could be made responsive to interest rates without greatly altering the conclusions of the model.

Meanwhile, the logarithmic utility of the households combined with the deposit constraint implies that:

$$p_t C_t = \frac{1}{(1+\omega_t)} r_{t-1} \bar{D} \qquad v_t X_t = \frac{\omega_t}{(1+\omega_t)} r_{t-1} \bar{D}$$

$$p_t \tilde{C}_t = \frac{1}{(1+\omega_t)} e_t \tilde{r}_{t-1} \tilde{D} \qquad v_t \tilde{X}_t = \frac{\omega_t}{(1+\omega_t)} e_t \tilde{r}_{t-1} \tilde{D}$$

which gives a straightforwad calculation of net-exports as:

$$\text{NX}_t(\omega) = \frac{\omega_t}{(1+\omega_t)} e_{t-1} \tilde{r}_{t-1} \tilde{D} - \frac{1}{(1+\omega_t)} r_{t-1} \bar{D} \tag{15}$$

As $\omega_t$ increases, U.S. consumers demand a higher share of oil in their consumption bundle, while oil-exporting country consumers desire a lower share of the consumption goods, leading to an increase in net exports. At the same time, prices of oil increase as global demand has increased.

Combining the balance sheets of oil-producing country consumers and the central bank we arrive at a condition relating net exports and financial flows:

$$\text{NX}_t(\omega) = e_t(B_t^C + \tilde{M}_t^C) - M_t + \bar{D} - (Q_t^C - r_{t-1}\bar{D}) \tag{16}$$

This relation implies that, for a fixed exchange rate, as $\omega_t$ increases (decreases), either the domestic central bank must increase (decrease) their net holdings of U.S. assets, inclusive of reserves held domestically by U.S. banks.

At this point, we make some simplifying assumptions in order to achieve analytical solutions. In particular, we assume that $\bar{e} = 1$, $\delta^\star = \bar{\delta}$ and that $Z_t$ and $\tilde{Z}_t$ are uniformly distributed over the interval $[-\chi_Z, \chi_Z]$, and with $S_t$ uniformly distributed over the interval $[-\chi_S, \chi_S]$ with $\chi_Z$ and $\chi_S$ large enough so that the probability of a deposit shock is non-zero over the range of $M_t$ and $\tilde{M}_t$ we consider. This reduces (14) to:

$$\bar{\delta} - \delta_t = \frac{c}{2\chi_Z} \left[ \theta(\tilde{D} - \bar{D}) - (\tilde{M}_t - M_t) \right]$$

substituting in to $\tilde{M}_t$ from the intermediary balance sheet gives us:

$$\bar{\delta} - \delta_t = \frac{c}{\chi Z}\left(M_t + \frac{1}{2}\left[B_t - (1-\theta)\tilde{D} - (1+\theta)\bar{D}\right]\right)$$

which relates the spread to bond holdings of the intermediary and the supply of reserves in the oil-producing country.

With this equation in hand, we turn to the oil-producing central banks' determination of reserves. Substituting in the above to (9), the oil producing country now sets deposits by:

$$M_t = \frac{\kappa}{2}\left[(1-\theta)\tilde{D} + (1+\theta)\bar{D} - B_t\right] \qquad \text{where} \quad \kappa = \kappa^\star\left(\frac{c}{\chi Z}\right)^2 1 + \kappa^\star\left(\frac{c}{\chi Z}\right)^2$$

Because the central bank places weight on a lower balance sheet, it does not act to completely offset flows of bonds onto intermediaries balance sheets that take up domestic reserves. This results in an equilibrium spread between U.S. and oil-producing country rates on reserves of:

$$\bar{\delta} - \delta_t = \frac{1}{2}(1-\kappa)\left[B_t - (1-\theta)\tilde{D} - (1+\theta)\bar{D}\right] = \theta(\tilde{r}_t - r_t)$$

As the central bank places more weight on meeting its interest rate target, an increase in intermediary holdings of Treasuries would cause a smaller widening of the interest-rate differential as the oil-producing central bank acts more forcefully in supplying domestic reserves to counteract the effect.

We can also pin down central banks' precautionary demand for loans to the Federal Reserve:

$$\tilde{M}_t^C = \frac{c}{\psi}\left(\frac{\chi S}{\chi Z}\right)\left[\bar{D} + (1-\theta)\tilde{D} - B_t - M_t\right]$$

This equality reflects the fact that both the oil-producing central bank and the intermediaries have a liquidity demand for balances with the U.S. central bank in the evening. As a dollar of liquidity becomes more valueable for the oil-producing central bank, in equilibrium they hold a greater amount.

The overall equilibrium effect of a shock to $\omega$ is determined by two equations. The first relates to the amount of Treasuries born by intermediaries to the equilbrium yield on Treasuries:

$$y_t = \frac{c}{2\chi_Z}\left(\left(1-\frac{\kappa}{2}\right)(B_t-(1-\theta)\bar{D})-[1-(1+\theta)\lambda]\,\tilde{D}\right)+\frac{1}{2}+\bar{\delta}$$

This equation comes from a combination of the first-order conditions for banks and the solution to oil-producing country reserve supply. The second equation represents the cost of bearing Treasuries for the U.S. household. From the balance of payments condition, substituting in the central banks' reserve decisions and holdings of Federal Reserve deposits we find:

$$\begin{aligned}\tilde{B}_t = \bar{B} &- \left(1+\frac{1}{\Psi}\right)\left(\left[1-\frac{\kappa}{2}\right]B_t - \left[1-(1+\theta)\frac{\kappa}{2}\right]\bar{D}\right)-(1-\theta)\left(\frac{\kappa}{2}-\frac{1}{\Psi}+\frac{\kappa}{2\Psi}\right)\tilde{D}\\ &-(Q_t^C - r_{t-1}\bar{D}) - \mathrm{NX}_t(\omega)\end{aligned}$$

where $\Psi = \frac{\psi\chi_Z}{c\chi_S}$. This relationship determines another curve relating Treasuries born by intermediaries to yields through the first-order condition for U.S. household holdings of Treasuries:

$$y_t = \frac{1}{\beta}\left(1-\frac{\rho}{\tilde{B}_t}\right)$$

We can think of this second curve as a net-supply curve of bonds to the intermediary (as quantity held by intermediaries increases, required yield decreases, or price rises) and the first curve as a net-demand curve (as quantity held by intermediaries increases, required yield increases, or price falls). The price in the demand curve (taking account of the bounds of the uniform distribution) is bounded between $\bar{\delta}$ and $\bar{\delta}+1$, while the net supply curve is bounded above by $\beta^{-1}$, and approaches negative infinity as $\tilde{B}_t$ approaches zero. Thus, all that is needed for an interior equilibrium where intermediaries do bear a strictly positive risk of a demand shock positive is that $\bar{\delta} < \beta^{-1} < \bar{\delta}+1$ and that $\tilde{B}_t < 0$ when $\chi_Z = \theta\bar{D} - \tilde{M}_t$.

With these two equations in hand, we can turn to analyzing a decrease in net exports. When net exports decrease it shifts the net-supply curve out, as the asymptote of the curve is:

$$B^{\star} = \frac{\bar{B}-\Pi_t-\mathrm{NX}_t(\omega)}{(1+\Psi^{-1})(1-\frac{\kappa}{2})}+\frac{1-(1+\theta)\frac{\kappa}{2}}{1-\frac{\kappa}{2}}\bar{D}-(1-\theta)\frac{\kappa}{2}\tilde{D}+\frac{\Psi^{-1}}{(1+\Psi^{-1})(1-\frac{\kappa}{2})}\tilde{D}$$

This shift leaves the net-demand curve unchanged, however. As a result, yields increase as do

Treasuries held by intermediaries. This leads to an increase in equilibrium money market spreads since $(1-\theta)(y_t - \bar{\delta}) = r_t - \bar{\delta}$. The interpretation is straightforward: as net exports fall, the oil-producing central bank is forced to sell Treasuries, some of which end up being purchase by intermediaries instead of reserves, leading to higher illiquidity. This is the main mechanism of interest for our paper. Further, the decrease in oil-producing country central bank holdings of Treasuries coincides with an increase of interest-rate differentials as the oil-producing country adjusts in part through lowering domestic reserves.

Finally, the size of the outward shift in the net-supply curve is determined by three factors. The first is $\rho$, which governs the elasticity of Treasury demand. The second and third are parameters governing the oil-producing central banks' decisions on asset holdings. First, as the oil-producing central bank cares more about its interest rate target ($\kappa \to 1$), the shock to net exports has a larger effect as the oil-producing central bank is unwilling to meet changes in net exports by altering the deposit rate. Second, the more the foreign central bank cares about domestic liquidity ($\Psi \to \infty$) the larger the effect, as the central bank is unwilling to meet changes in net exports by decrease its holdings of deposits with the Federal Reserve.

In summary, this model shows a simple example of our main mechanism. As oil-producing countries face negative shocks to oil demand, they are forced to sell Treasuries onto the hands of U.S. investors in order to maintain the balance of payments. Simultaneously, interest-rate differentials rise to the extent that the central bank does not fully adjust their supply of domestic reserves. For a fixed central bank objective function, the larger the size of Treasury sales, the higher the interest-rate differential. The increase in Treasuries sold to the intermediary is larger (and the increase in interest-rate differentials smaller) the more weight the oil-exporting central bank places on keeping domestic interest rates at target. With Federal Reserve policy held fixed, sales of these Treasuries lead to a decrease in U.S. liquidity and an increase in money market spreads as intermediaries and U.S. investors become burdened with Treasuries and face a decrease in available reserves. With these conclusions in hand, we proceed to an examination of the empirical relationship between oil prices, foreign reserve management, and U.S. liquidity.

# 5 Empirical analysis

## 5.1 Identification strategy

For the large oil-exporting countries in our 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 relationship 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 our 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 our 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.[5]

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 unlikely that the oil exporters in our 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 our sample period by scraping press releases from the OPEC website based on Känzig's (2020) work. 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.

There may be several additional concerns about omitted variables. We control for a wealth of factors that have been shown to affect repo rates. One particular concern may be that oil volatility affects the repo market through other channels. This could occur indirectly if both repo spreads and oil volatility are driven by U.S. macroeconomic cycles. With the daily data, however, we are primarily focused on variation associated with high-frequency news. We therefore control for macro news announcements using the Citigroup Economic Surprise Index, for FOMC announce-

[5]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.

ments that might represent news relevant to money markets, and for the VIX to represent financial volatility more broadly.

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 our sample countries, since it is based on U.S. prices, however as the primary oil futures contract trade in the U.S. it is arguably more 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. This helps to clarify our channel where oil volatility increases leading oil producers to adjust their reserve holdings from an alternative channel where oil price volatility increases leading to increased risk of defaultt.

### 5.2 Repo data

We collect a daily series of repo rate spreads, exchange rate differentials, and Brent option-implied volatility to test the mechanism implied by our model. Figure 8 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. First, 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. Second, the difference between the GCF index and the interest rate on excess reserves gives a narrower picture of inter-dealer spreads. Third, 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 like 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 like 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. First, we can explain a large share (around 70%) of the first principal component of exchange rate differences in the first stage regressions. As Figure 7 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 these 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 1st, 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 Inspecting the mechanism

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 relationship 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.

First, we examine the relationship between interest rate differentials and Treasury holdings. Table 16 displays the results of regressions using the TIC data, which is monthly and therefore provides fewer observations in the estimation. We first examine the effects on Treasury holdings by sample countries. 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 7. 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 16 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 19, 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 16. 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 suggest 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.

One alternative method of obtaining 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 this 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 our 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 present a confirmation of 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 our 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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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.

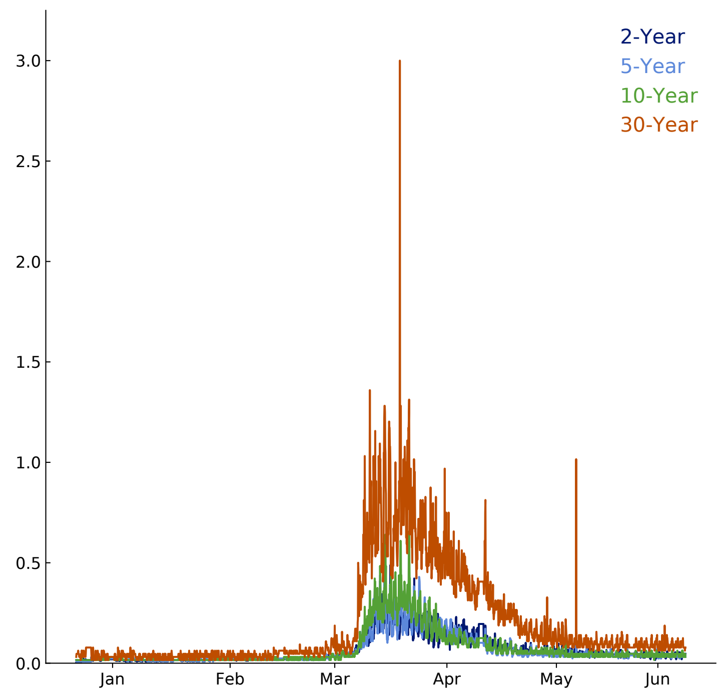

Figure 2: **Foreign official sales and dollar liquidity.** This figure shows foreign official Treasury holdings, swap lines, and investments into the foreign repo pool as reported in the Federal Reserve's Factors Affecting Reserves release. All values are differences from their values as of March 1st,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

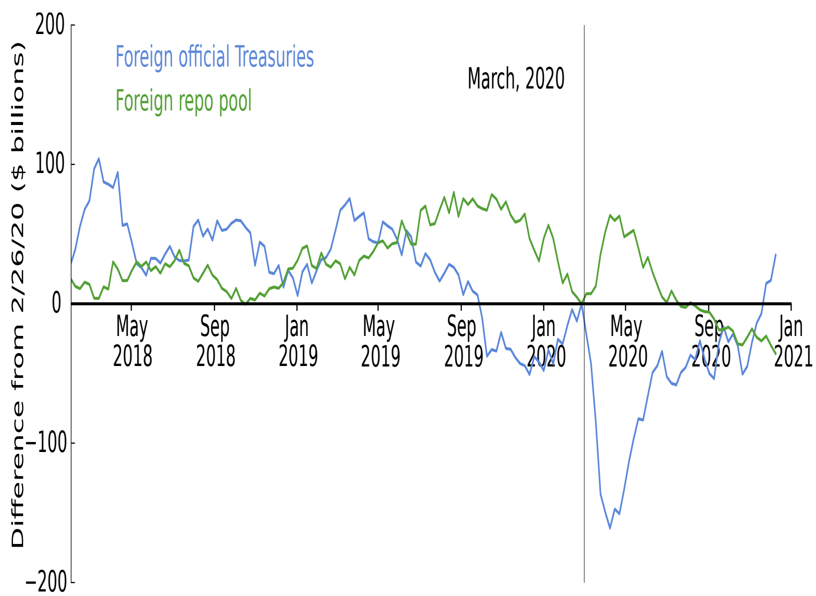

Figure 3: **Diagram depicting sales by domestic mutual funds and sales by foreign central banks.** Arrows denote the flow of cash or securities. The top panel examines the effects of sales by mutual funds. The bottom panel examines the effects of sales by foreign central banks which are invested in the 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.

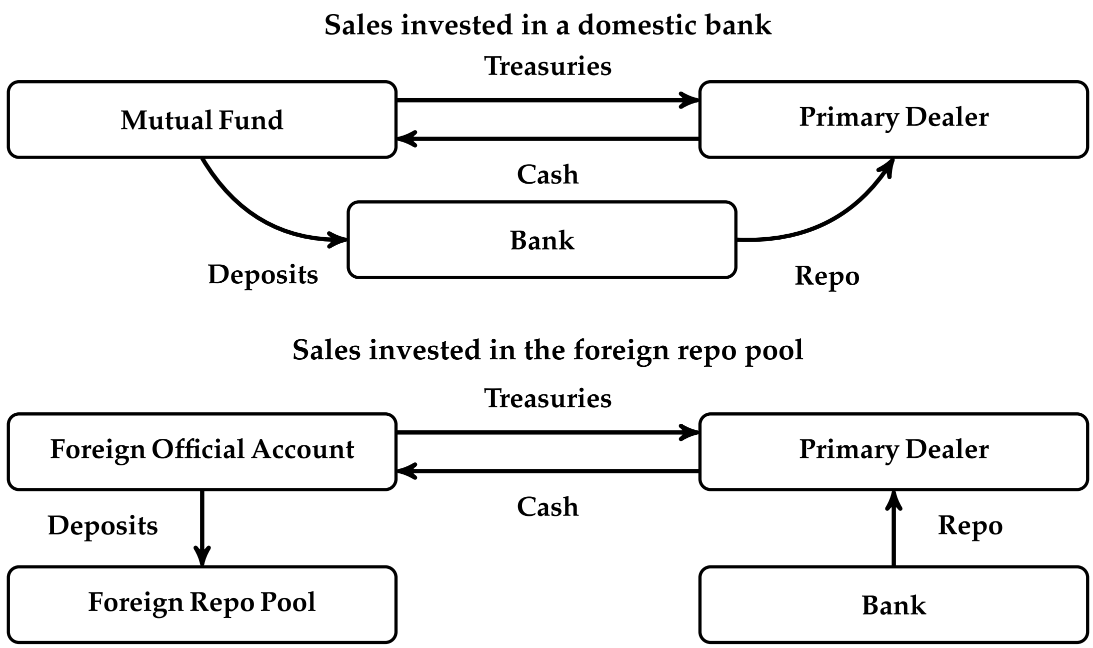

Figure 4: **Treasury sales in March 2020.** Sales are the difference between positions at the end of February and end of March for total Treasuries using the TIC major foreign holders of Treasuries data.

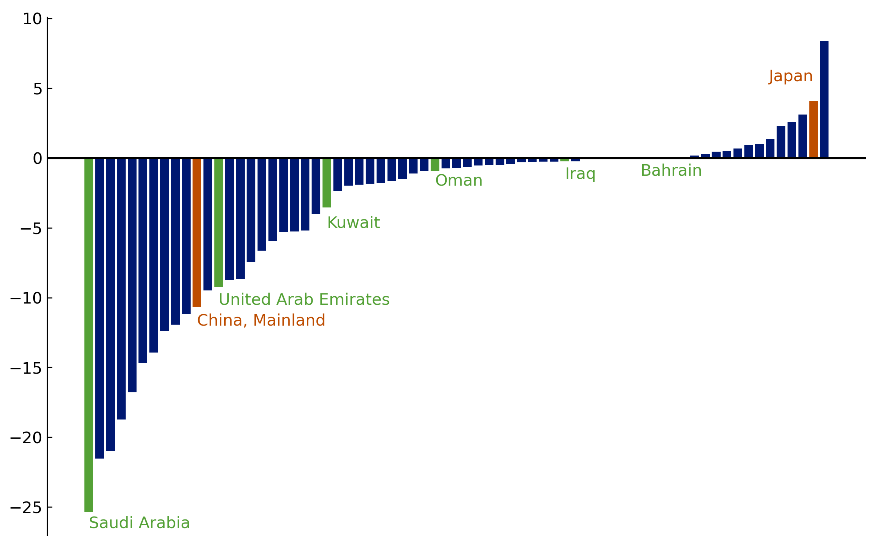

Figure 5: **Location of sample countries.** The five countries in our sample of major oil exporter TIC countries with pegged exchange rates are highlighted in green.

Figure 6: **Implied interest rate differentials across sample countries.** Daily implied differentials from forward and spot exchange rates

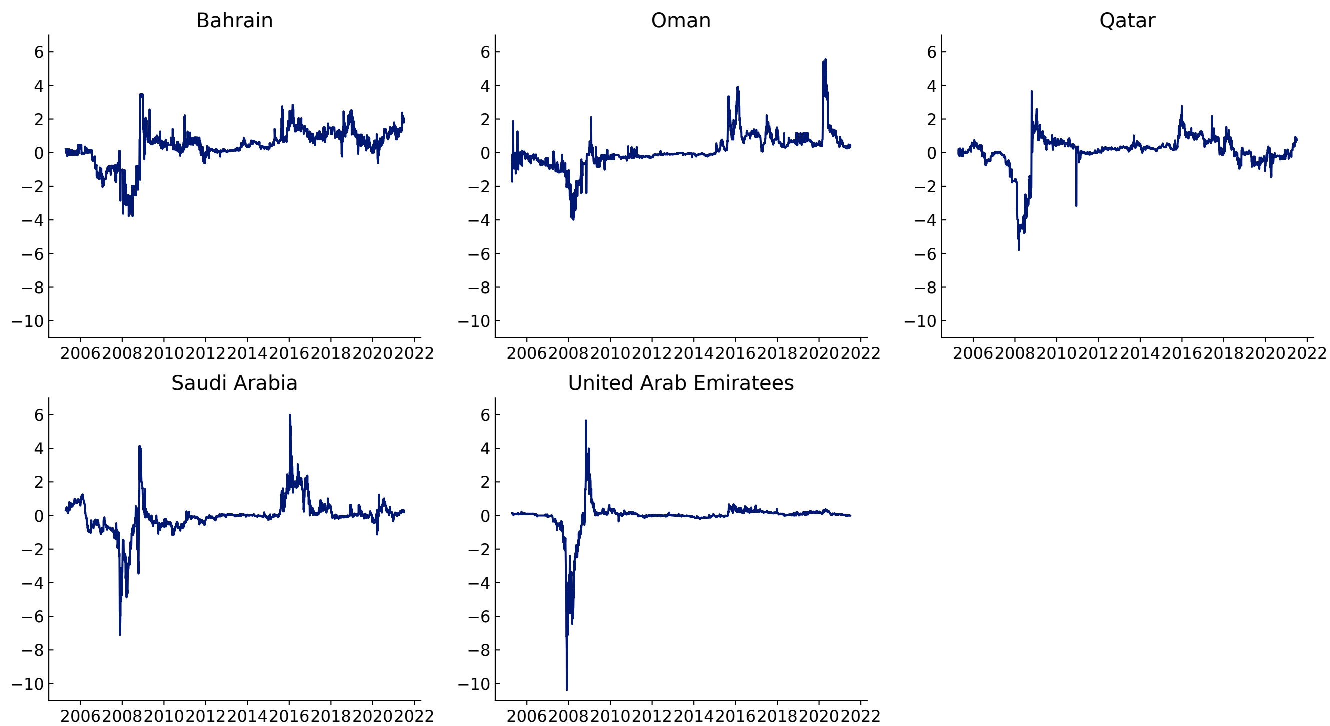

Figure 7: **Implied interest rate differentials, oil volatility and Treasury sales.** This figure shows daily data on Brent option-implied volatility from at-the-money options along with daily data on interest rate differentials implied by exchange rate spot and forward swap prices and month data on 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 within this time frame so that values can be easily compared.

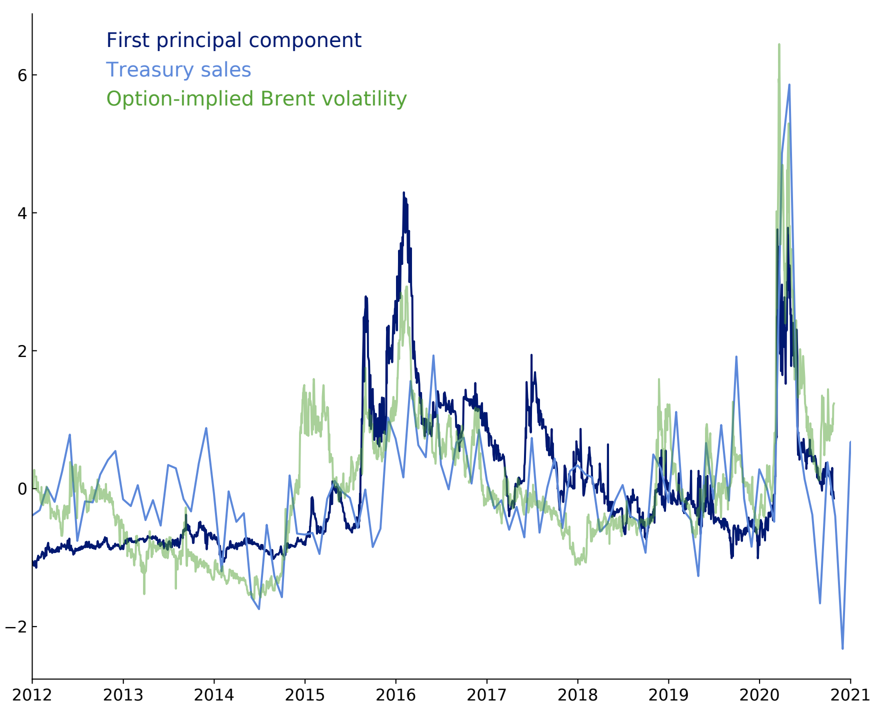

Figure 8: **Diagram of money markets and money market rate aggregates.** Arrows denote the flow of cash from cash lenders to cash borrowers. Dashed lines denote unsecured funding, while solid lines denote secured funding. For secured funding, securities flow in the opposite direction of the solid lines. Colored boxes denote the ranges of transaction each rate employed in this paper covers.

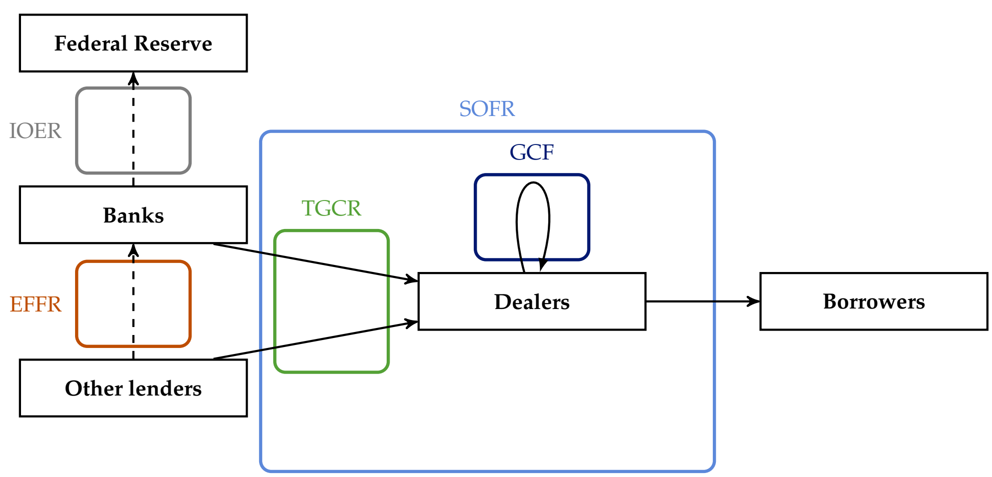

Table 1: **Total Treasury sales by group.** This table shows total sales, long-term Treasury sales and short-term Treasury sales by country groups from the TIC holdings table in March 2020. Amounts are in billions of dollars. High oil production countries are countries in the top third of the TIC sample 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** | $\approx 2$ | 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 our five sample 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.**

| VARIABLES | (1) SOFR - IOER | (2) GCF - IOER | (3) GCF - TGCR | (4) GCF - EFFR |
|---|---|---|---|---|
| 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) |
| Bond issuance | -0.002 | -0.000 | -0.002 | -0.000 |
| | (0.002) | (0.002) | (0.002) | (0.002) |
| T-bill yield | -0.003*** | -0.003*** | -0.003*** | -0.003*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| TGA balances | 0.002*** | 0.003*** | 0.002*** | 0.003*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Month-end dummy | 0.054 | 0.057 | 0.054 | 0.057 |
| | (0.101) | (0.077) | (0.101) | (0.077) |
| Income tax payment | 0.002 | 0.001 | 0.002 | 0.001 |
| | (0.003) | (0.003) | (0.003) | (0.003) |
| SOMA purchases | -0.007** | 0.005** | -0.007** | 0.005** |
| | (0.003) | (0.003) | (0.003) | (0.003) |
| SOMA sales | 0.688 | 0.009 | 0.688 | 0.009 |
| | (1.013) | (0.008) | (1.013) | (0.008) |
| OPEC Announcement | 1.201 | 1.391 | 1.202 | 1.391 |
| | (1.609) | (1.615) | (1.609) | (1.615) |
| WTI margin | -0.001*** | -0.000*** | -0.001*** | -0.000*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| VIX | -0.005 | -0.030*** | -0.005 | -0.030*** |
| | (0.003) | (0.002) | (0.003) | (0.002) |
| CESI | -0.004*** | -0.003*** | -0.004*** | -0.003*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| FOMC | -0.018 | -0.023 | -0.018 | -0.023 |
| | (0.057) | (0.045) | (0.057) | (0.045) |
| CDS Saudi Arabia | 2.080*** | 0.989*** | 2.080*** | 0.989*** |
| | (0.090) | (0.072) | (0.090) | (0.072) |
| Brent return | 1.509*** | 0.372 | 1.509*** | 0.372 |
| | (0.424) | (0.408) | (0.424) | (0.408) |
| *Oil price volatility* | 0.055*** | 0.057*** | 0.055*** | 0.057*** |
| | (0.003) | (0.002) | (0.003) | (0.002) |
| Constant | 0.362*** | 0.041 | 0.362*** | 0.041 |
| | (0.085) | (0.059) | (0.085) | (0.059) |
| Observations | 1,380 | 2,488 | 1,379 | 2,488 |
| R-squared | 0.745 | 0.692 | 0.745 | 0.692 |

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.

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

| VARIABLES | (1)<br>SOFR - IOER | (2)<br>GCF - IOER | (3)<br>GCF - TGCR | (4)<br>GCF - EFFR |
|---|---|---|---|---|
| *IR factor* | 2.294** | 5.252*** | 3.680*** | 2.598*** |
| | (1.065) | (0.764) | (0.586) | (0.656) |
| 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) |
| Bond issuance | 0.039 | 0.040 | 0.030 | 0.039 |
| | (0.050) | (0.042) | (0.028) | (0.036) |
| T-bill yield | 0.112*** | 0.118*** | 0.006 | 0.042*** |
| | (0.007) | (0.005) | (0.004) | (0.005) |
| TGA balances | -0.007 | -0.016*** | -0.004* | -0.005 |
| | (0.004) | (0.004) | (0.002) | (0.003) |
| Month-end dummy | 4.560** | 2.783* | 2.551** | 6.854*** |
| | (2.055) | (1.625) | (1.131) | (1.394) |
| Income tax payment | 0.064 | 0.084 | 0.062* | 0.090* |
| | (0.063) | (0.054) | (0.035) | (0.046) |
| SOMA purchases | -0.223*** | -0.131** | -0.129*** | -0.243*** |
| | (0.061) | (0.053) | (0.034) | (0.046) |
| SOMA sales | -21.925 | 0.173 | -20.299* | 0.206 |
| | (20.590) | (0.172) | (11.335) | (0.147) |
| OPEC Announcement | -31.179 | -125.920*** | -109.119*** | -104.252*** |
| | (32.705) | (34.019) | (18.005) | (29.192) |
| WTI margin | 0.006*** | 0.003*** | -0.000 | 0.002*** |
| | (0.001) | (0.000) | (0.000) | (0.000) |
| VIX | 0.220*** | 0.138*** | -0.081** | 0.032 |
| | (0.068) | (0.045) | (0.038) | (0.038) |
| CESI | 0.033*** | 0.029*** | 0.016** | 0.017*** |
| | (0.012) | (0.007) | (0.006) | (0.006) |
| FOMC | 3.632*** | 3.138*** | 0.461 | 2.558*** |
| | (1.158) | (0.943) | (0.638) | (0.809) |
| CDS Saudi Arabia | -4.188 | -1.861 | -1.249 | 2.588 |
| | (3.380) | (2.012) | (1.861) | (1.727) |
| Brent return | -10.242 | -5.810 | 3.393 | -1.582 |
| | (8.757) | (8.597) | (4.821) | (7.377) |
| Constant | -42.723*** | -26.099*** | 10.311*** | -7.663*** |
| | (1.939) | (1.255) | (1.069) | (1.077) |
| Observations | 1,380 | 2,488 | 1,379 | 2,488 |
| R-squared | 0.384 | 0.276 | 0.157 | 0.133 |
| IV F-stat | 363.2 | 758.6 | 362.6 | 758.6 |

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.

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

| VARIABLES | (1) SOFR - IOER | (2) GCF - IOER | (3) GCF - TGCR | (4) GCF - EFFR |
|---|---|---|---|---|
| *IR factor* | -1.956*** | -0.319 | 1.127*** | 0.257 |
| | (0.415) | (0.260) | (0.241) | (0.215) |
| 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) |
| Bond issuance | 0.031 | 0.039 | 0.025 | 0.039 |
| | (0.032) | (0.034) | (0.035) | (0.029) |
| T-bill yield | 0.090*** | 0.093*** | -0.008** | 0.032*** |
| | (0.007) | (0.006) | (0.003) | (0.006) |
| TGA balances | 0.006* | 0.009*** | 0.004** | 0.005** |
| | (0.003) | (0.002) | (0.002) | (0.002) |
| Month-end dummy | 4.493*** | 2.842* | 2.507 | 6.875*** |
| | (1.480) | (1.487) | (1.808) | (1.509) |
| Income tax payment | 0.074* | 0.099** | 0.067 | 0.095** |
| | (0.040) | (0.049) | (0.046) | (0.041) |
| SOMA purchases | -0.215*** | -0.088** | -0.124*** | -0.226*** |
| | (0.033) | (0.036) | (0.033) | (0.032) |
| SOMA sales | -16.275*** | 0.207 | -16.928** | 0.220** |
| | (4.114) | (0.137) | (6.588) | (0.088) |
| 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) |
| CESI | 0.007 | 0.006 | 0.000 | 0.007 |
| | (0.015) | (0.007) | (0.006) | (0.006) |
| FOMC | 3.647 | 2.941 | 0.471 | 2.475 |
| | (3.435) | (2.509) | (1.053) | (2.343) |
| CDS Saudi Arabia | 7.527*** | 9.210*** | 5.789*** | 7.247*** |
| | (1.805) | (1.183) | (1.197) | (0.981) |
| Brent return | -3.415 | -3.778 | 7.538 | -0.652 |
| | (13.217) | (12.880) | (5.565) | (11.845) |
| Constant | -37.807*** | -22.917*** | 13.283*** | -6.326*** |
| | (2.758) | (1.530) | (1.062) | (1.388) |
| 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.

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

| VARIABLES | (1) SOFR - IOER | (2) GCF - IOER | (3) GCF - TGCR | (4) GCF - EFFR |
|---|---|---|---|---|
| *IR factor* | 1.770* | 5.578*** | 3.452*** | 2.629*** |
| | (1.026) | (0.884) | (0.569) | (0.755) |
| 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) |
| Bond issuance | 0.035 | 0.021 | 0.011 | 0.026 |
| | (0.053) | (0.044) | (0.029) | (0.037) |
| T-bill yield | 0.102*** | 0.115*** | 0.002 | 0.038*** |
| | (0.007) | (0.006) | (0.004) | (0.005) |
| TGA balances | 0.009** | -0.011** | 0.003 | 0.002 |
| | (0.004) | (0.005) | (0.002) | (0.004) |
| Month-end dummy | 5.079** | 3.121* | 2.809** | 7.089*** |
| | (2.072) | (1.662) | (1.149) | (1.419) |
| Income tax payment | 0.057 | 0.089 | 0.070** | 0.088* |
| | (0.063) | (0.055) | (0.035) | (0.047) |
| SOMA purchases | 3.187*** | 0.322* | -0.560 | 0.017 |
| | (0.855) | (0.165) | (0.474) | (0.141) |
| SOMA sales | -19.324 | 0.250 | -20.407* | 0.238 |
| | (20.092) | (0.175) | (11.144) | (0.150) |
| OPEC Announcement | -62.203 | -117.627** | -90.127*** | -85.745** |
| | (48.321) | (50.181) | (26.804) | (42.851) |
| WTI margin | 0.006*** | 0.004*** | 0.000 | 0.002*** |
| | (0.001) | (0.000) | (0.000) | (0.000) |
| VIX | 0.149* | 0.113** | -0.061 | 0.034 |
| | (0.088) | (0.056) | (0.049) | (0.048) |
| CESI | 0.008 | 0.021*** | 0.014** | 0.012* |
| | (0.012) | (0.007) | (0.007) | (0.006) |
| FOMC | 4.225*** | 3.424*** | 0.128 | 2.733*** |
| | (1.186) | (0.980) | (0.658) | (0.837) |
| CDS Saudi Arabia | -3.324 | -2.285 | -1.603 | 2.133 |
| | (3.308) | (2.243) | (1.835) | (1.916) |
| Brent return | -18.719 | -17.090 | -4.442 | -15.790 |
| | (14.217) | (13.102) | (7.887) | (11.189) |
| Constant | -47.481*** | -27.922*** | 7.751*** | -9.960*** |
| | (2.250) | (1.444) | (1.250) | (1.233) |
| Observations | 1,299 | 2,407 | 1,298 | 2,407 |
| R-squared | 0.430 | 0.265 | 0.168 | 0.141 |
| IV F-stat | 402.1 | 600.1 | 401.4 | 600.1 |

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.

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

| VARIABLES | (1)<br>SOFR - IOER | (2)<br>GCF - IOER | (3)<br>GCF - TGCR | (4)<br>GCF - EFFR |
|---|---|---|---|---|
| *IR factor* | 4.614*** | 5.781*** | 2.397*** | 4.154** |
| | (1.529) | (1.950) | (0.809) | (1.827) |
| Bill issuance | 0.004** | 0.007*** | 0.003*** | 0.007*** |
| | (0.002) | (0.003) | (0.001) | (0.002) |
| Note issuance | 0.011 | 0.020** | 0.012*** | 0.019** |
| | (0.008) | (0.010) | (0.004) | (0.009) |
| Bond issuance | 0.040 | 0.040 | 0.007 | 0.044 |
| | (0.057) | (0.072) | (0.030) | (0.068) |
| T-bill yield | 0.123*** | 0.124*** | -0.006 | 0.052*** |
| | (0.010) | (0.013) | (0.005) | (0.012) |
| TGA balances | 0.008* | 0.007 | 0.004* | 0.007 |
| | (0.004) | (0.006) | (0.002) | (0.005) |
| Month-end dummy | 5.544** | 6.796** | 3.090*** | 12.216*** |
| | (2.246) | (2.861) | (1.186) | (2.681) |
| Income tax payment | 0.066 | 0.120 | 0.087** | 0.116 |
| | (0.072) | (0.092) | (0.038) | (0.086) |
| SOMA purchases | 2.608** | 2.404* | -0.049 | 0.134 |
| | (1.045) | (1.331) | (0.552) | (1.247) |
| SOMA sales | -19.367 | -30.614 | -19.936* | -29.695 |
| | (21.186) | (26.979) | (11.187) | (25.280) |
| OPEC Announcement | -72.175 | -127.753* | -88.778*** | -101.809* |
| | (51.728) | (65.882) | (27.318) | (61.734) |
| WTI margin | 0.008*** | 0.008*** | -0.001 | 0.005*** |
| | (0.001) | (0.001) | (0.001) | (0.001) |
| VIX | 0.011 | -0.025 | -0.021 | 0.060 |
| | (0.107) | (0.136) | (0.057) | (0.128) |
| CESI | 0.015 | 0.024 | 0.009 | 0.019 |
| | (0.013) | (0.017) | (0.007) | (0.016) |
| FOMC | 4.303*** | 4.733*** | 0.140 | 4.248*** |
| | (1.299) | (1.654) | (0.686) | (1.550) |
| CDS Saudi Arabia | -9.229** | -9.063* | 0.990 | -2.034 |
| | (4.235) | (5.401) | (2.240) | (5.061) |
| Brent return | -21.936 | -25.638 | -2.552 | -22.268 |
| | (15.252) | (19.426) | (8.055) | (18.203) |
| Constant | -54.374*** | -46.277*** | 10.464*** | -23.213*** |
| | (3.302) | (4.218) | (1.749) | (3.952) |
| Observations | 1,213 | 1,212 | 1,212 | 1,212 |
| R-squared | 0.392 | 0.262 | 0.175 | 0.131 |
| IV F-stat | 215.1 | 214.3 | 214.3 | 214.3 |

Table **??** 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.

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) |
| 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) |
| Bond issuance | 0.072 | 0.039 | 0.036 | 0.001 | 0.012 | -0.011 |
| | (0.045) | (0.030) | (0.034) | (0.316) | (0.307) | (0.127) |
| 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) |
| TGA balances | 0.004 | -0.000 | 0.005 | -0.146*** | -0.120** | -0.025 |
| | (0.007) | (0.005) | (0.005) | (0.052) | (0.051) | (0.021) |
| Income tax payment | -0.500 | -0.715 | 0.319 | -8.765 | -6.795 | -1.970 |
| | (1.362) | (0.893) | (1.026) | (9.429) | (9.174) | (3.788) |
| SOMA purchases | -0.022 | -0.029*** | 0.007 | -0.330*** | -0.312*** | -0.018 |
| | (0.014) | (0.009) | (0.011) | (0.105) | (0.102) | (0.042) |
| SOMA sales | 0.024 | -0.020 | 0.043 | 133.735* | 172.645** | -38.910 |
| | (0.045) | (0.030) | (0.034) | (70.741) | (68.826) | (28.421) |
| OPEC Announcement | -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) |
| CESI | -0.003 | -0.005 | 0.003 | -0.240* | -0.350*** | 0.111** |
| | (0.016) | (0.011) | (0.012) | (0.132) | (0.128) | (0.053) |
| 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) |
| 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) |
| Brent return | 42.819 | 1.292 | 39.459 | 100.651 | -46.363 | 147.014* |
| | (31.863) | (20.903) | (24.006) | (218.174) | (212.269) | (87.654) |
| Constant | 12.756*** | 6.514** | 6.206* | -91.377*** | -59.865* | -31.512** |
| | (4.306) | (2.825) | (3.244) | (32.040) | (31.173) | (12.872) |
| R2 | 0.64 | 0.73 | 0.21 | 0.56 | 0.56 | 0.26 |
| N | 94 | 94 | 94 | 71 | 71 | 71 |
| IV F-stat | 42.33 | 42.33 | 42.33 | 37.01 | 37.01 | 37.01 |

Table 16 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.

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) |
| 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) |
| Bond issuance | 0.075 | 0.038 | 0.040 | -0.054 | -0.025 | -0.029 |
| | (0.047) | (0.030) | (0.034) | (0.298) | (0.307) | (0.115) |
| 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) |
| TGA balances | 0.006 | 0.003 | 0.004 | -0.135*** | -0.108** | -0.027 |
| | (0.008) | (0.005) | (0.006) | (0.052) | (0.054) | (0.020) |
| Income tax payment | -0.591 | -0.654 | 0.157 | -10.814 | -8.147 | -2.667 |
| | (1.410) | (0.917) | (1.033) | (9.025) | (9.312) | (3.488) |
| SOMA purchases | -0.115* | -0.072* | -0.043 | -0.923* | -0.593 | -0.330* |
| | (0.060) | (0.039) | (0.044) | (0.517) | (0.533) | (0.200) |
| SOMA sales | 0.033 | -0.016 | 0.047 | 173.282** | 195.883*** | -22.600 |
| | (0.049) | (0.032) | (0.036) | (68.157) | (70.324) | (26.340) |
| OPEC Announcement | -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) |
| CESI | -0.001 | -0.005 | 0.006 | -0.302** | -0.390*** | 0.088* |
| | (0.017) | (0.011) | (0.012) | (0.126) | (0.130) | (0.049) |
| 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) |
| 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) |
| Brent return | 43.225 | 21.309 | 22.492 | 146.889 | 51.108 | 95.781 |
| | (38.763) | (25.203) | (28.411) | (239.738) | (247.364) | (92.649) |
| Constant | 10.253* | 5.937 | 3.899 | -57.694 | -38.917 | -18.776 |
| | (5.642) | (3.669) | (4.136) | (42.385) | (43.734) | (16.380) |
| R2 | 0.22 | 0.29 | 0.16 | 0.41 | 0.36 | 0.15 |
| N | 90 | 90 | 90 | 67 | 67 | 67 |
| IV F-stat | 32.27 | 32.27 | 32.27 | 23.46 | 23.46 | 23.46 |

Table 16 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.

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

| VARIABLES | (1) Dealer Treasuries | (2) Custody holdings | (3) Foreign repo | (4) Swap lines |
|---|---|---|---|---|
| *IR factor* | 3.078 | -7.375* | 5.054*** | 0.143 |
| | (2.232) | (4.259) | (1.222) | (2.146) |
| 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) |
| Bond issuance | -0.050 | -0.032 | 0.031 | -0.101** |
| | (0.049) | (0.094) | (0.027) | (0.047) |
| T-bill yield | 0.053*** | -0.010 | 0.023*** | -0.061*** |
| | (0.016) | (0.030) | (0.009) | (0.015) |
| TGA balances | -0.015 | -0.089*** | -0.025*** | 0.074*** |
| | (0.012) | (0.023) | (0.007) | (0.012) |
| Month-end dummy | -4.061 | -4.800 | 9.666*** | 2.820 |
| | (4.314) | (8.232) | (2.362) | (4.149) |
| Income tax payment | 0.032 | 0.887*** | 0.023 | 0.047 |
| | (0.178) | (0.340) | (0.098) | (0.171) |
| SOMA purchases | -0.129*** | -0.213*** | 0.071*** | 0.633*** |
| | (0.037) | (0.071) | (0.020) | (0.036) |
| SOMA sales | 0.832*** | 0.429 | -0.240* | -0.089 |
| | (0.236) | (0.450) | (0.129) | (0.227) |
| OPEC Announcement | -54.812 | 471.929* | -111.298 | -400.761*** |
| | (137.384) | (262.177) | (75.213) | (132.133) |
| WTI margin | 0.000 | -0.006** | 0.003*** | 0.002 |
| | (0.001) | (0.003) | (0.001) | (0.001) |
| VIX | 0.967*** | -0.459* | -0.048 | -0.114 |
| | (0.140) | (0.267) | (0.077) | (0.135) |
| CESI | -0.040* | -0.091** | -0.049*** | -0.032 |
| | (0.022) | (0.043) | (0.012) | (0.022) |
| FOMC | 0.029 | -0.127 | 1.368 | 0.181 |
| | (2.064) | (3.940) | (1.130) | (1.986) |
| CDS Saudi Arabia | -6.460 | 13.847 | 3.969 | 6.207 |
| | (5.972) | (11.397) | (3.270) | (5.744) |
| Brent return | -10.037 | -36.059 | 34.891** | 198.607*** |
| | (27.451) | (52.387) | (15.029) | (26.402) |
| Constant | -0.349 | 26.638*** | -8.143*** | -46.388*** |
| | (4.643) | (8.861) | (2.542) | (4.466) |
| Observations | 522 | 522 | 522 | 522 |
| R-squared | 0.212 | 0.266 | 0.320 | 0.776 |
| IV F-stat | 172.1 | 172.1 | 172.1 | 172.1 |

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.

Table 18: **First stage of instrumental variables regressions for repo spreads.**

| VARIABLES | (1) SOFR - IOER | (2) GCF - IOER | (3) GCF - TGCR | (4) GCF - EFFR |
|---|---|---|---|---|
| *IR factor* | 1.770* | 5.578*** | 3.452*** | 2.629*** |
| | (1.026) | (0.884) | (0.569) | (0.755) |
| 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) |
| Bond issuance | 0.035 | 0.021 | 0.011 | 0.026 |
| | (0.053) | (0.044) | (0.029) | (0.037) |
| T-bill yield | 0.102*** | 0.115*** | 0.002 | 0.038*** |
| | (0.007) | (0.006) | (0.004) | (0.005) |
| TGA balances | 0.009** | -0.011** | 0.003 | 0.002 |
| | (0.004) | (0.005) | (0.002) | (0.004) |
| Month-end dummy | 5.079** | 3.121* | 2.809** | 7.089*** |
| | (2.072) | (1.662) | (1.149) | (1.419) |
| Income tax payment | 0.057 | 0.089 | 0.070** | 0.088* |
| | (0.063) | (0.055) | (0.035) | (0.047) |
| SOMA purchases | 3.187*** | 0.322* | -0.560 | 0.017 |
| | (0.855) | (0.165) | (0.474) | (0.141) |
| SOMA sales | -19.324 | 0.250 | -20.407* | 0.238 |
| | (20.092) | (0.175) | (11.144) | (0.150) |
| OPEC Announcement | -62.203 | -117.627** | -90.127*** | -85.745** |
| | (48.321) | (50.181) | (26.804) | (42.851) |
| WTI margin | 0.006*** | 0.004*** | 0.000 | 0.002*** |
| | (0.001) | (0.000) | (0.000) | (0.000) |
| VIX | 0.149* | 0.113** | -0.061 | 0.034 |
| | (0.088) | (0.056) | (0.049) | (0.048) |
| CESI | 0.008 | 0.021*** | 0.014** | 0.012* |
| | (0.012) | (0.007) | (0.007) | (0.006) |
| FOMC | 4.225*** | 3.424*** | 0.128 | 2.733*** |
| | (1.186) | (0.980) | (0.658) | (0.837) |
| CDS Saudi Arabia | -3.324 | -2.285 | -1.603 | 2.133 |
| | (3.308) | (2.243) | (1.835) | (1.916) |
| Brent return | -18.719 | -17.090 | -4.442 | -15.790 |
| | (14.217) | (13.102) | (7.887) | (11.189) |
| Constant | -47.481*** | -27.922*** | 7.751*** | -9.960*** |
| | (2.250) | (1.444) | (1.250) | (1.233) |
| Observations | 1,299 | 2,407 | 1,298 | 2,407 |
| R-squared | 0.430 | 0.265 | 0.168 | 0.141 |
| IV F-stat | 402.1 | 600.1 | 401.4 | 600.1 |

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.

Table 19: **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* | -3.842** | -3.283*** | -0.656 | -10.297 | -15.026 | 4.730 |
| | (1.692) | (1.100) | (1.240) | (12.354) | (12.747) | (4.774) |
| 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) |
| Bond issuance | 0.075 | 0.038 | 0.040 | -0.054 | -0.025 | -0.029 |
| | (0.047) | (0.030) | (0.034) | (0.298) | (0.307) | (0.115) |
| 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) |
| TGA balances | 0.006 | 0.003 | 0.004 | -0.135*** | -0.108** | -0.027 |
| | (0.008) | (0.005) | (0.006) | (0.052) | (0.054) | (0.020) |
| Income tax payment | -0.591 | -0.654 | 0.157 | -10.814 | -8.147 | -2.667 |
| | (1.410) | (0.917) | (1.033) | (9.025) | (9.312) | (3.488) |
| SOMA purchases | -0.115* | -0.072* | -0.043 | -0.923* | -0.593 | -0.330* |
| | (0.060) | (0.039) | (0.044) | (0.517) | (0.533) | (0.200) |
| SOMA sales | 0.033 | -0.016 | 0.047 | 173.282** | 195.883*** | -22.600 |
| | (0.049) | (0.032) | (0.036) | (68.157) | (70.324) | (26.340) |
| OPEC Announcement | -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) |
| CESI | -0.001 | -0.005 | 0.006 | -0.302** | -0.390*** | 0.088* |
| | (0.017) | (0.011) | (0.012) | (0.126) | (0.130) | (0.049) |
| 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) |
| 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) |
| Brent return | 43.225 | 21.309 | 22.492 | 146.889 | 51.108 | 95.781 |
| | (38.763) | (25.203) | (28.411) | (239.738) | (247.364) | (92.649) |
| Constant | 10.253* | 5.937 | 3.899 | -57.694 | -38.917 | -18.776 |
| | (5.642) | (3.669) | (4.136) | (42.385) | (43.734) | (16.380) |
| R2 | 0.22 | 0.29 | 0.16 | 0.41 | 0.36 | 0.15 |
| N | 90 | 90 | 90 | 67 | 67 | 67 |
| IV F-stat | 32.27 | 32.27 | 32.27 | 23.46 | 23.46 | 23.46 |

Table 16 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.