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Nonlinear Dynamics of Gold and the Dollar

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Abstract

Notwithstanding the widely held view that gold and the dollar are negatively correlated, we ask when and why gold and the dollar sometimes depart from their typical inverse relationship and go so far as to move in parallel. Using a threshold vector error correction model (VECM), we investigate the nonlinear relationship between gold and the dollar. We find evidence of short run positive correlation between gold and the dollar under extreme market conditions. Our result suggests that the hedging property of gold is influenced by the gold-dollar threshold process.

Keywords: gold; exchange rate; nonlinear dynamics; threshold cointegration

JEL: F31, G15

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1 Introduction

A negative correlation between the price of gold and the value of the U.S. dollar has been widely noted (Beckers & Soenen, 1984; Capie et al., 2005; Sjaastad & Scacciavillani, 1996). Nevertheless, recent findings give rise to several debates that can hardly be reconciled by extant literature. First, despite the well-recognized negative correlation between gold and the dollar, there have been increasing observations showing this relationship can sometimes be disturbed and the two series move towards the same direction[2]. This is intuitively puzzling since under the law of one price, if gold is priced with respect to a world numeraire, its price in an appreciating currency should decrease. Second, while gold is believed to be a hedge against the US dollar (Harris & Shen, 2017; Pukthuanthong & Roll, 2011), its role as a safe haven during the extreme period is far more equivocal[3]. The previous studies have found contrasting relationship between gold and dollar around financial turbulence period (Ciner et al., 2013; Joy, 2011; Reboredo, 2013; Reboredo & Rivera-Castro, 2014). These raise the question of whether the usual gold-dollar relationship is preserved, and how this relationship changes during extreme market conditions. This paper attempts to reconcile these issues by investigating the nonlinear dynamics between gold and the U.S. dollar.

We begin by documenting the dynamics of gold price and the U.S. dollar exchange rate in both long run and short run, as well as across tranquil and turbulent market conditions. It shows that, consistent with the law of one price, gold and the U.S. dollar maintain a negative relationship in the long run. In other words, gold price expressed in dollar terms rises when the dollar depreciates. Nevertheless, this stable relationship can sometimes be disturbed in the short run, especially during periods of dramatic price movements. Closer inspection of the gold-dollar

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[2] Mining analyst *James Fraser* pointed out in 2013, "Fluctuations in the U.S. dollar do not always show a negative correlation with the price of gold." (James Fraser. How the Price of Gold Reflects the Value of the U.S. Dollar. Available at <http://www.kitco.com/ind/Fraser/2013-11-11-How-the-Price-of-Gold-Reflects-the-Value-of-the-US-Dollar.html>, accessed on Aug. 2, 2018). Similarly, the *Mining Stock Journal* noticed in October 2016 that gold and the dollar could move in tandem in the short run, stating "One interesting occurrence that has not been written about in the precious metals alternative media or blog space yet is that gold has been quietly moving in tandem with the dollar over the past several trading sessions." (Mining Stock Journal. Gold And The Dollar Moving In Tandem? Available at <http://investmentresearchdynamics.com/gold-and-the-Dollar-moving-in-tandem/>, accessed on Aug. 2, 2018). Market analyst Paul Robinson also argued, "While it's true the correlation between the metal and currency has been inverted over the long-run … the relationship does flip from time to time and the two will move in tandem." (Paul Robinson. Can the U.S. dollar & Gold Price Advance Together? Sure They Can… Available at <https://www.dailyfx.com/forex/technicalarticle/special_report/2017/09/04/Can-the-US-Dollar-Gold-Price-Advance-Together-Sure-They-Can-PRtech.html, accessed on Aug. 2, 2018).

[3] The definitions of "hedge" and "safe haven" are given in Kaul & Sapp (2006) and Baur & McDermott (2010), where a "hedge" asset is uncorrelated or negatively correlated with another asset or portfolio on average, while a "safe haven" asset is uncorrelated or negatively correlated with another asset or portfolio at times of extreme market movements.

dynamics found that anomalies usually occurred during periods of major financial turbulence, energy crises and political instability. These anomalies under extreme market conditions suggest the existence of nonlinear relationship in the gold-dollar dynamics.

In an effort to reconcile short-run deviations from the long-run inverse relationship, as well as to characterize transitional behaviors of the gold-dollar dynamics across typical and extreme market conditions, we estimate a two-regime threshold vector error correction model (threshold VECM). We adopt the techniques of Balke & Fomby (1997) and Hansen & Seo (2002), in which the basic idea is that the approach allows for discontinuous adjustments to the long-run equilibrium. Using monthly data of gold price and U.S. dollar index from 1976 to 2017, we find an inverse relationship between gold and the dollar in the typical regime, where a 1% increase in the dollar's value depresses gold price by 3.09%. A short-run positive correlation is also confirmed in the case of the extreme regime, once gold price and the dollar deviate too far from their long-run equilibrium.

We obtain similar results across various specifications. Our results remain robust after controlling for the additional variables, e.g. the global economic uncertainty, the economic cycle and the interest-rate differentials between countries. Finally, we find that there is still a threshold cointegration relationship between gold and the U.S. dollar even after accounting for the financial market turmoil, reinforcing our findings that the threshold dynamics of the gold-dollar relationship truly arise from unobservable threshold process.

Our paper makes two contributions to the literature. First, our study reconciles the in-tandem movement observed in the market and the negative gold-dollar relationship grounded on economic theories (Baur & Glover, 2015; Białkowski et al. 2015; Zagaglia & Marzo, 2013; Zhao et al., 2015). The positive correlation occurs as a result of discontinuous adjustments to the gold-dollar long-run equilibrium. These findings are particularly pertinent for portfolio investments, in which assets should have low correlation or even negative correlations. Our results suggest that investors can include gold in their US dollar's assets portfolio, as gold could serve as a dollar assets hedge in tranquil market conditions, but this is not the case during periods of major financial turbulence. The gold-dollar relationship is perturbed in extreme market conditions, weakening gold's hedging role against exchange rate fluctuations (Białkowski et al., 2015; Zagaglia & Marzo, 2013). Thus, we contribute to the literature of studying gold's role as exchange rate hedge as well as portfolio investments (Ciner et al., 2013; Joy, 2011; Reboredo, 2013; Reboredo & Rivera-Castro, 2014).

Our work also contributes to the studies of gold's safe-haven property. Studies by Capie et al. (2005), Ciner et al. (2013), and Reboredo (2013) suggest that gold can be both a hedge and a safe haven against the US dollar, whereas Joy (2011) and Reboredo & Rivera-Castro (2014) find gold to be a poor safe haven. Moreover, recent studies point out that the previous findings are biased due to sample selection (Barro & Misra, 2016; Erb & Harvey, 2013; Harris & Shen, 2017). Our empirical results suggest that gold's safe-haven property is influenced by the threshold process. In the typical regime, the safe-haven role of gold is preserved. Thus, empirical research during typical-regime periods are more likely to find that gold acts as a safe haven against the U.S. dollar. There are not such properties under extreme market conditions.

The remainder of the paper is organized as follows. Section 2 briefly reviews extant literature investigating the gold-dollar relationship. Section 3 documents the dynamics of gold price and the U.S. dollar exchange rate in the long run and the short run, and across typical and extreme regimes. Section 4 introduces our research design. Empirical results and interpretations are then presented in section 5, followed by robustness checks in section 6. Finally, section 7 concludes.

2 Literature Review

Exchange rates have been perceived as one of the macroeconomic fundamentals influencing the price of gold (Dooley et al., 1995; Harris & Shen, 2017; Sjaastad, 2008; Sjaastad & Scacciavillani, 1996). And the dollar, as the dominant international currency and the major currency denominating gold, plays an increasingly important role (Sjaastad, 2008).

Acknowledging the close ties between gold and the U.S. dollar, many researchers have investigated the gold-dollar dynamics, in which an inverse relationship is generally found (Beckers & Soenen, 1984; Capie et al., 2005; Pukthuanthong & Roll, 2011). Beckers & Soenen (1984) provide early empirical evidence of the opposite movement between gold price and dollar exchange rates. Noting that the depreciation of dollar tends to result in an immediate rise in the dollar price of gold. Sjaastad & Scacciavillani (1996) and Sjaastad (2008) put forth an international pricing model linking the long-term relationship between gold and exchange rates. The model shows that the price spread of an internationally-traded commodity including gold between different reference currencies is due to the fluctuations of exchange rates. The excess demand for the commodity in a specific currency is a function of its price and other market fundamental factors. Global market-clearing of the excess demand in different currencies results in a long-term negative relationship between the price of commodities and their priced currencies. Capie et al. (2005) assess the extent to which gold acts as a hedge against the U.S. dollar over a thirty-year period, in which they find a negative and typically inelastic relationship between the two. Pukthuanthong & Roll (2011) study gold price and its denominated currencies and conclude that a rising gold price is associated with currency depreciation, which holds not only for the U.S. dollar but also in the case of the euro, pound sterling, and yen.

The gold-dollar relationship is also under much scrutiny from the standpoint of portfolio diversification (Ciner et al., 2013; Joy, 2011; Reboredo, 2013; Reboredo & Rivera-Castro, 2014). While basically all research agree that gold can act as a hedge against the U.S. dollar, its role as a safe haven during extreme market conditions is far more equivocal. Ciner et al. (2013) show that gold can be both a hedge and a safe haven against the U.S. dollar, whereas Joy (2011) finds gold to be a poor safe haven. Moreover, some recent papers argue that the findings may be sample-specific, calling into question credibility of past research (Barro & Misra, 2016; Erb & Harvey, 2013; Harris & Shen, 2017). The gold-dollar relationship is also challenged by the recent global financial crisis (Zagaglia & Marzo, 2013). Zagaglia & Marzo (2013) examine the gold-dollar relationship in times of crisis, in which they find disproportionate reactions of gold prices and the U.S. dollar towards exogenous increases in market uncertainty, suggesting the pattern of the gold-dollar dynamics could deviate from the tranquil period.

In order to address these concerns in the extant literature, our study investigates the nonlinear dynamics between gold and the U.S. dollar using a threshold model in a similar manner as in Balke & Fomby (1997), Chong et al. (2008), and Hansen & Seo (2002). The idea of threshold cointegration was first proposed by Balke & Fomby (1997) to allow for nonlinear adjustments to long-run equilibrium. Later, Hansen & Seo (2002) propose a method to empirically implement the Maximum Likelihood Estimation (MLE) of the model, and test for the presence of a threshold effect when the cointegrating vector is unknown. This method is particularly pertinent to our research since it can reconcile long-run inverse relationship and short-run nonlinear adjustments in the gold-dollar dynamics, allowing the pattern to switch across regimes.

3 A Glance at the Gold-Dollar Dynamics

3.1 Long-Run Inverse Relationship and Short-Run Deviations

In the long run, gold and the U.S. dollar are negatively correlated and seem to maintain an equilibrium. As shown in Figure 1, the monthly data of gold price and the U.S. dollar index from Jan. 1976 to Dec. 2017 generally move in opposite directions throughout the entire period, both in nominal and real terms. In addition, as presented in Table 1, the distribution of positive and negative rolling-window correlations between gold and the dollar, calculated based on different time intervals ranging from 3 months to 10 years, also suggests that for a majority of time gold and the dollar are negatively correlated (73% for the 3-month interval and as high as 95% for the 10-year interval).

Yet, positive correlations are present for a certain amount of time in the short run, occupying around one fifth of the sample period. The distribution based on different time intervals given in Table 1 indicates that during longer time spans gold and the dollar are generally negatively correlated, while if examined in shorter periods positive correlations could more likely be found.

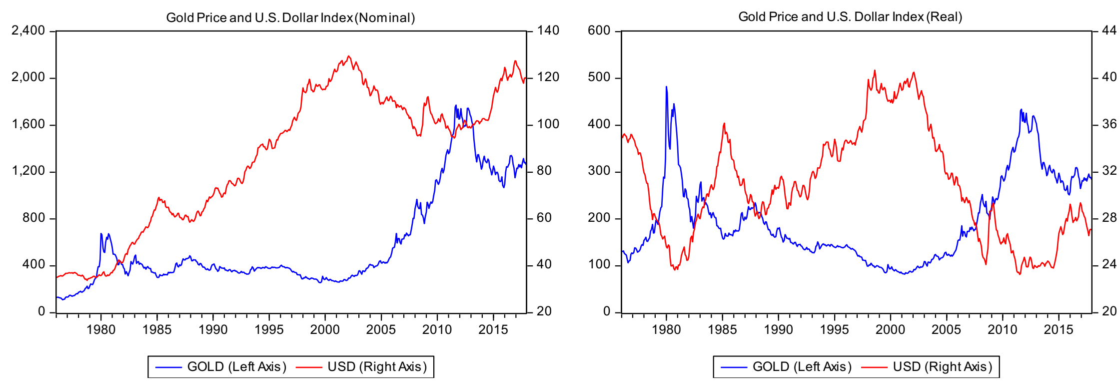

Fig. 1: Gold Price and the U.S. Dollar Index Dynamics (Jan. 1976-Dec. 2017)

Note. This figure presents the dynamics of monthly average gold price and the U.S. dollar index from Jan. 1976 to Dec. 2017 in both nominal and real terms. The long-term inverse relationship between gold and the U.S. dollar is pretty obvious throughout the sample period. The nominal gold price series is the monthly average of daily gold fixing prices per troy ounce (3:00 p.m., London time) in London Bullion Market quoted in the U.S. dollar. The nominal U.S. dollar series is the monthly average of the daily U.S. dollar index, which is a weighted average of the foreign exchange value of the U.S. dollar against currencies of a broad group of major U.S. trading partners. The real series are obtained from deflating the nominal series with the U.S. consumer price index, taking the first month in the sample as the base period. The data of gold price, the U.S. dollar index, and the U.S. consumer price index are obtained from the FRED Economic Data.

Table 1: Distribution of Rolling-Window Correlations Between Gold Price and the U.S. Dollar Index

Interval		3-Month	6-Month	1-Year	5-Year	10-Year
Count	Positive	136	100	88	79	19
	Negative	366	399	405	366	366
Percentage	Positive	27%	20%	18%	18%	5%
	Negative	73%	80%	82%	82%	95%

Note. This table reports the distribution of positive and negative rolling-window correlations between gold and the dollar, calculated based on different time intervals ranging from three months to ten years. It suggests that for a majority of time gold and the dollar are negatively correlated (73% for the 3-month interval and as high as 95% for the 10-year interval).

3.2 Anomalies During Extreme Market Conditions

The occurrence of positive correlation is especially frequent during periods of market turbulence. Figure 2 shows positive rolling-window correlations between gold and the dollar during a 3-month time interval, along with major financial, energy or political incidents that are expected to have an influence on the gold-dollar relationship. Highly positive correlations (between 0.8 to 1) are found in the wake of the ratification of the Jamaica Agreement in Jan. 1976, during the 1979-1980 political instability and the second energy crisis, in the Latin American debt crisis that happened in Aug. 1982, in the months following the fall of the Berlin Wall in Nov. 1989, in the course of the 1990 oil price shock, throughout the Yugoslav Wars that began with the Ten-Day war in Slovenia in Jun. 1991 and reached a climax in the first half of 1999 when NATO bombed Yugoslavia, as well as during various crises, namely the Asian financial crisis occurring in the last two quarters of 1997, Argentina's debt default in Jan. 2002, the outbreak of the Iraq war in Mar. 2003, the 2007-2009 subprime mortgage crisis, the European Crisis and the Arab Spring occurring between 2010 and 2011, the rise to global prominence of the terrorist organization ISIL during the first half of 2014, and the Brexit referendum in Jun. 2016. Relatively high positive correlations are found for the few months after the Plaza Accord was signed (with the correlation being 0.41), as well as during the peak of the Dotcom Bubble in Mar. 2000 (with the correlation being 0.61) and the 911 Attack in 2001 (with the correlation being 0.70).

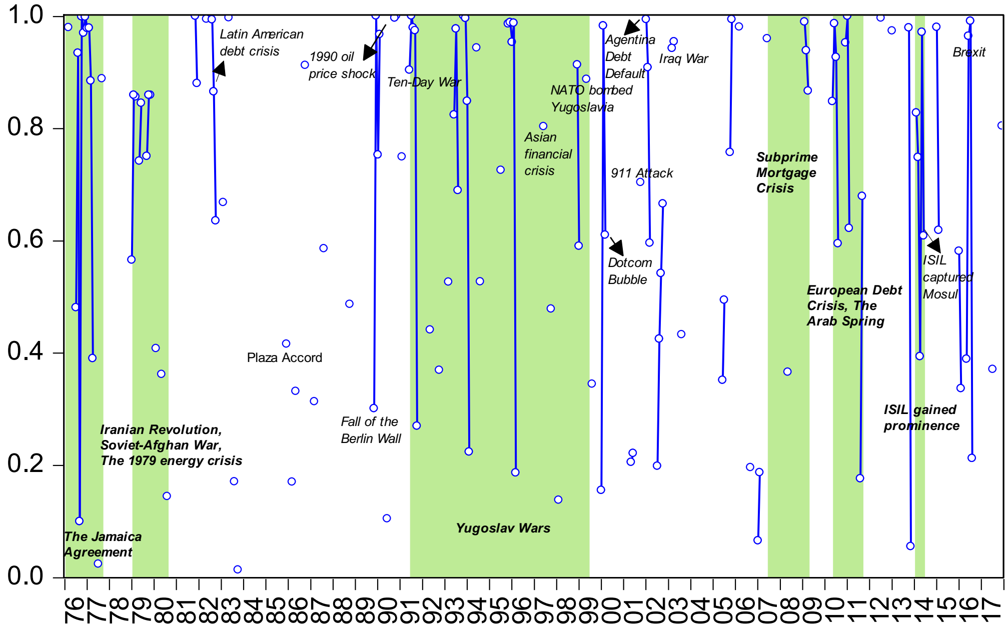

Fig. 2: Positive 3-Month Rolling-Window Correlations Between Gold and the Dollar with Major Events

Note. This figure presents the positive rolling-window correlations between gold and the dollar with a 3-month time interval, along with major financial, energy or political incidents that are expected to have an influence on the gold-dollar relationship.

4 Research Design

As first suggested by Sjaastad & Scacciavillani (1996), the cointegration relationship between the U.S. dollar and gold prices is implicitly related to the law of one price applied to gold. If the gold is expressed with respect to some world numeraire, then its price in a depreciating currency will rise (Pukthuanthong & Roll, 2011). Along this line, Sjaastad (2008) finds the U.S dollar bloc dominates the world gold market, and that there is a long-run negative relationship between the U.S dollar and the gold prices.

Based on our observation, we explore the possibility of nonlinear adjustments to the long-run equilibrium between gold and the dollar. In tranquil times, gold and the dollar maintain a long-run negative relationship, and the hedging property of gold is preserved. In contrast, at times of turmoil, gold price or exchange rate movements become so volatile that the two variables deviate too much from their long-run equilibrium. Under such circumstances, short-run positive interactions between gold and the dollar may be found, and the role of gold as an exchange rate hedge may be debilitated.

To characterize the nonlinear gold-dollar dynamics, we adopt the threshold VECM technique from Balke & Fomby (1997) and Hansen & Seo (2002).

Let g_t and e_t denote gold price and the U.S. dollar exchange rate respectively. Both g_t and e_t are nonstationary I(1) time series but nonetheless maintain a stable long-run relationship cointegrating in β. The cointegrating equation is

$$g_t = \beta e_t + constant \tag{1}$$

where in the long run we expect β to be negative, indicating that a 1% increase in the dollar's value will dampen gold price by β.

Rearranging the cointegrating equation, we obtain the error-correction term $w_t(\beta) = g_t - \beta e_t$, termed *gold-dollar deviation* thereafter. The gold-dollar deviation measures the level of deviation from the long-run equilibrium between gold price and U.S. dollar exchange rate. And the coefficient of the gold-dollar deviation reveals the speed of reversion back to equilibrium.

Further, let Z_t denote an $\mathrm{n} \times 1$ vector of exogenous variables, which are fundamental variables influencing gold price and the dollar exchange rate. Let p denote the order of lags of autoregressive variables. Let Δ be the first difference operator.

Consider a linear VECM

$$\begin{pmatrix} \Delta \mathrm{g}_t \\ \Delta \mathrm{e}_t \end{pmatrix} = \beta_0 + \beta_1 w_{t-1}(\beta) + \beta_{21} \begin{pmatrix} \Delta \mathrm{g}_{t-1} \\ \Delta \mathrm{e}_{t-1} \end{pmatrix} + \cdots + \beta_{2p} \begin{pmatrix} \Delta \mathrm{g}_{t-p} \\ \Delta \mathrm{e}_{t-p} \end{pmatrix} + \beta_3 Z_t + \mathrm{u}_t \tag{2}$$

where the dimensions of β_0 and β_1 are 2×1, $\beta_{21}, \cdots \beta_{2p}$ are 2×2, and β_3 is $2 \times \mathrm{n}$. The error term u_t is assumed to be a 2×1 vector white noise sequence with a finite covariance matrix. Equation (2) is referred to as a linear VECM because coefficients do not vary among the values of $w_{t-1}(\beta)$. In other words, no matter how large in magnitude the gold-dollar deviation is away from the long-run equilibrium, the gold-dollar dynamics move in the manner as they usually do, irrespective of market conditions.

To account for transitional behaviors of the gold-dollar dynamics across typical and extreme regimes, we allow coefficients to take different values depending on whether the gold-dollar deviation exceeds the threshold. The threshold VECM is

$$\begin{pmatrix} \Delta \mathrm{g}_t \\ \Delta \mathrm{e}_t \end{pmatrix} = \begin{cases} \beta_0^T + \beta_1^T w_{t-1}(\beta) + \beta_{21}^T \begin{pmatrix} \Delta \mathrm{g}_{t-1} \\ \Delta \mathrm{e}_{t-1} \end{pmatrix} + \cdots + \beta_{2p}^T \begin{pmatrix} \Delta \mathrm{g}_{t-p} \\ \Delta \mathrm{e}_{t-p} \end{pmatrix} + \beta_3^T Z_t + \mathrm{u}_t^T, \; g_t - \beta e_t > \gamma \\ \beta_0^E + \beta_1^E w_{t-1}(\beta) + \beta_{21}^E \begin{pmatrix} \Delta \mathrm{g}_{t-1} \\ \Delta \mathrm{e}_{t-1} \end{pmatrix} + \cdots + \beta_{2p}^E \begin{pmatrix} \Delta \mathrm{g}_{t-p} \\ \Delta \mathrm{e}_{t-p} \end{pmatrix} + \beta_3^E Z_t + \mathrm{u}_t^E, \; g_t - \beta e_t \leq \gamma \end{cases} \tag{3}$$

where superscripts T and E stand for the typical regime and the extreme regime respectively, and γ denotes the threshold.

5 Empirical Results

5.1 Data

The sample period extends from Jan. 1976, the time when the Jamaica Agreement was signed, to Dec. 2017. A total of 504 valid observations are included in the sample.

The main series under examination are monthly data of gold price and the U.S. dollar index in real terms. We first collect the monthly average of daily gold fixing price per troy ounce (3:00 p.m., London time) in London Bullion Market quoted in the U.S. dollar, and daily U.S. dollar index which is a weighted average of the foreign exchange value of the U.S. dollar against currencies of a broad group of major U.S. trading partners. These two series are then deflated using the U.S. consumer price index, taking the first month in the sample as the base period. All data, including gold price, the U.S. dollar index and the U.S. consumer price index, are obtained from FRED Economic Data. Further, we take natural logarithms of gold price and the dollar index and denote these two series as lg and le, respectively. We then take the logarithmic difference of gold price and the dollar index to obtain the change rate of these two variables and denote these two series as Δlg and Δle, respectively.

We also control for other fundamental variables influencing gold price and the dollar exchange rate. As observed in Sjaastad (2008), the price of gold is dominated by U.S. market power, implying U.S. fundamentals exert substantial impacts on gold price (McKinnon, 2014; Meltzer, 2013). First, we include U.S. interest rates in our model, taking the effective federal funds rate as the proxy (Barsky & Summers, 1988; Erb & Harvey, 2013). Second, we employ S&P 500 as a proxy for stock market return to account for returns of alternative investment assets (Hillier et al., 2006; Solnik, 1987). Finally, we include the U.S. industrial production index, unemployment rate, and money supply (M1) as proxies for macroeconomic fundamentals (Meese & Rose, 1990; Obstfeld & Stockman, 1985). Table 2 reports the descriptions and sources of exogenous variables. Table 3 presents the descriptive statistics of all variables included in the model.

Table 2: Exogenous Variables

Variables	Description	Source
Ir	Effective federal funds rate	Board of Governors of the Federal Reserve System (US)
M1	The change rate of U.S. M1 money stock	
Ip	The change rate of U.S. Industrial Production Index	
Stock	The change rate of S&P 500	Yahoo Finance
Ur	U.S. civilian unemployment rate	U.S. Bureau of Labor Statistics

Note. This table reports the denotations, description, and sources of exogenous variables.

Table 3: Descriptive Statistics

Variables	Mean	Max	Min	Std.	Skew.	Kurt.
Δlg	0.0015	0.3804	-0.1990	0.0458	1.2206	10.638
Δle	-0.0005	0.0748	-0.0417	0.0136	0.4014	1.7313
Ir	5.0596	19.1000	0.0700	0.1809	0.8622	0.8544
M1	5.9562	6.7095	5.5379	0.0123	0.9999	0.6279
Stock	5.3322	6.3984	4.1331	0.0285	-0.2347	-1.3523
Ip	3.3548	3.8110	3.1110	0.0073	1.3867	1.7304
Ur	6.3591	11.4000	3.6000	0.0719	0.6651	-0.1771

Note. This table reports the descriptive statistics of variables in the model. Δlg and Δle represent the change rates of gold price and the dollar index, respectively; Ir is the effective federal funds rate; M1 is the change rate of the U.S. M1 money stock; Stock is the change rate of the S&P 500; Ip is the change rate of the U.S. industrial production index; and Ur is the U.S. unemployment rate. Kurtosis reported in the table are normalized, taking the kurtosis of the standard normal distribution to be 0.

5.2 Estimation of the Linear VECM

We perform several preliminary tests before constructing and estimating the model. First, we conduct unit root tests to verify the stationarity of the two series. The results show that both gold price and the U.S. dollar index are I(1) processes. Therefore, further cointegration tests can be performed. Second, we determine the optimal lag order using information criteria. We follow the majority rule and select the optimal lag order of 3 in the unrestricted VAR model. Since the cointegration test is a restricted test on first-differenced variables, the lag order should be one less than that in the unrestricted VAR model. Thus, we select 2 as the optimal lag order in the cointegration test. Finally, we perform the Johansen cointegration test, the result of which suggests the presence of a long-run equilibrium relationship between gold price and the U.S. dollar index.

Then, we proceed to construct linear VECMs to characterize the long-run equilibrium and short-run adjustment behaviors in the gold-dollar dynamics. We first construct linear VECMs with only endogenous variables, namely gold price and the dollar exchange rate. Since the price of gold and the dollar exchange rate are also determined by other fundamentals, to avoid problems of missing variables, we then include exogenous variables in the VECMs. In case including exogenous variables interferes with the cointegration relationship and results of model selection, we repeat the above preliminary tests. Model selection criteria suggest the same result, and the cointegration test again confirms the presence of a long-run equilibrium relationship among these variables[4]. Then, we estimate linear VECMs with exogenous variables. The estimation results of linear VECMs with and without exogenous variables are reported in Table 4. The coefficient estimates and significance levels are similar in both models. Notably, the goodness-of-fit in the dollar equation increased from 18.38% to 25.92% after including exogenous variables.

Table 4: Estimation Results of Linear VECM

	(1)		**(2)**	
	$\Delta \mathrm{lg}_t$	$\Delta \mathrm{le}_t$	$\Delta \mathrm{lg}_t$	$\Delta \mathrm{le}_t$
$\mathbf{w_{t-1}}$	-0.0235*	-0.0088***	-0.0207*	-0.0104***
	(-1.95)	(-2.63)	(-1.73)	(-3.29)
$\mathbf{\Delta lg_{t-1}}$	0.2116***	0.0035	0.2054***	0.0007
	(4.46)	(0.27)	(4.31)	(0.06)
$\mathbf{\Delta lg_{t-2}}$	-0.1421***	0.0164	-0.1483***	0.0197
	(-2.98)	(1.24)	(-3.09)	(1.56)
$\mathbf{\Delta le_{t-1}}$	-0.1929	0.4572***	-0.1865	0.4128***
	(-1.13)	(9.64)	(-1.07)	(8.99)
$\mathbf{\Delta le_{t-2}}$	0.0050	-0.0511	-0.0059	-0.0139
	(0.03)	(-1.07)	(-0.03)	(-0.30)
Constant	0.0013	-0.0003	0.0037	-0.0029
	(0.67)	(-0.63)	(0.44)	(-1.33)
Ir			-0.0010**	0.0003*
			(-1.96)	(1.88)
M1			0.0655	-0.0004
			(0.54)	(-0.01)
Stock			-0.0092	-0.0580***
			(-0.16)	(-3.86)
Ip			-0.2322	0.4582***
			(-0.84)	(6.28)
Ur			0.0004	0.0003
			(0.29)	(0.99)
Co. Equation	$lg = -2.98le + 15.38$		$lg = -3.07le + 15.70$	
Adj. R-squared	0.0608	0.1838	0.0596	0.2579

Note. This table reports the results of linear VECMs with and without exogenous variables. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Values in parentheses are *t*-Statistics. Δlg and Δle represent the change rates of gold price and the dollar index, respectively; w_{t-1} is the error correction term (the gold-dollar deviation); Ir is the effective federal funds rate; M1 is the change rate of the U.S. M1 money stock; Stock is the change rate of S&P 500; Ip is the change rate of the U.S. industrial production index; and Ur is the U.S. unemployment rate.

[4] The results of all tests are available upon request.

5.3 Estimation of the Threshold VECM

Next, we estimate the two-regime threshold VECM. As the first step, we conduct the SupLM test proposed by Hansen & Seo (2002) to check for the presence of threshold cointegration. The results significantly reject the null hypothesis, indicating that gold and the dollar do maintain a threshold cointegration relationship. Then, we take the optimal lag length of 2 and estimate the threshold VECM. Table 5 reports the estimation results of the threshold VECM.

First, gold and the dollar maintain a long-run inverse relationship, where a 1% appreciation of the U.S. dollar will result in a 3.09% decrease in gold price. Note that coefficients in the cointegrating equation of the threshold model are similar to those in the linear models, indicating that our estimations are quite robust.

Second, empirical results also confirm the presence of transitional behaviors during typical and extreme conditions, since the significance and the magnitude of coefficients vary greatly across regimes. During typical conditions, the gold-dollar dynamics manifest a mean-reverting pattern in the short run, as evidenced by the fact that the coefficient of the gold-dollar deviation is significantly negative in the gold equation. But the magnitude of the coefficient is rather small, implying slow reversion back to equilibrium. This is consistent with previous results with linear models (Levin & Wright, 2006). In addition, both gold and the U.S. dollar seem to relate closely to their own lagged values, despite the absence of interactions between gold and the U.S. dollar in the short run. When it comes to the extreme regime, the error-correction mechanism is disrupted, and gold price no longer follows its usual autoregressive pattern. Moreover, while interactions between gold and the U.S. dollar are absent in the typical regime, significant positive interactions between the two are found in the extreme regime. The typical regime and the extreme regime comprise 94.81% and 5.19% of the sample period, respectively.

Third, the positive correlation between gold and the U.S. dollar is indeed identified in the short run during the extreme regime. In the extreme regime, the coefficient of the second-order lagged gold price is significant and positive in the dollar equation, indicating that gold and the U.S. dollar can sometimes move in tandem once they depart too far from their long-run equilibrium relationship and falls into the extreme regime. This provides evidence of short-run deviations from the conventional inverse relationship between gold and the U.S. dollar, which is partly related to extreme market conditions.

Table 5: Estimation Results of the Threshold VECM

	Typical Regime		Extreme Regime	
	Δlg_t	Δle_t	Δlg_t	Δle_t
$\mathbf{w_{t-1}}$	-0.0334**	-0.0045	0.1475	-0.1205
	(-2.57)	(-1.29)	(0.48)	(-0.88)
$\mathbf{\Delta lg_{t-1}}$	0.2256***	0.0074	-0.4521	0.0656
	(2.91)	(0.69)	(-1.48)	(0.52)
$\mathbf{\Delta lg_{t-2}}$	-0.1724**	0.0162	-0.0985	0.1611**
	(-2.48)	(1.28)	(-0.53)	(2.58)
$\mathbf{\Delta le_{t-1}}$	-0.1789	0.4089***	-0.0027	0.4594**
	(-0.97)	(9.90)	(0.00)	(2.18)
$\mathbf{\Delta le_{t-2}}$	0.0125	-0.0315	-0.6616	0.2606
	(0.08)	(-0.73)	(-0.71)	(1.14)
Constant	0.5260**	0.0696	-2.1999	1.8428
	(2.55)	(1.25)	(-0.46)	(0.87)
Ir	-0.0009	0.0003*	0.0016	-0.0005
	(-1.23)	(1.93)	(0.55)	(-0.45)
M1	0.0589	-0.0270	0.4159	0.3096**
	(0.48)	(-0.90)	(0.79)	(2.40)
Stock	-0.0485	-0.0370**	0.0691	-0.1206
	(-0.68)	(-2.04)	(0.32)	(-1.32)
Ip	-0.3603	0.4895***	1.1075**	0.5936***
	(-1.13)	(6.49)	(2.09)	(3.49)
Ur	0.0011	0.0001	-0.0141**	0.0043
	(0.89)	(0.29)	(-2.19)	(1.57)
Co. Equation	$lg_{t-1} = -3.09le_{t-1} + 15.47$			
Threshold	$lg_{t-1} + 3.09le_{t-1} > 15.47$		$lg_{t-1} + 3.09le_{t-1} \leq 15.47$	
Observations	94.81 %		5.19%	
SupLM test statistic	39.0194			
P-value	0.0000			

Note. This table reports the estimation results of the threshold VECM. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Values in parentheses are *t*-Statistics. Δlg and Δle represent the change rates of gold price and the dollar index, respectively; w_{t-1} is the error correction term (the gold-dollar deviation); Ir is the effective federal funds rate; M1 is the change rate of the U.S. M1 money stock; Stock is the change rate of S&P 500; Ip is the change rate of the U.S. industrial production index; and Ur is the U.S. unemployment rate. SupLM test statistic under the null hypothesis H0 of linear cointegration and P-value come from Hansen and Seo (2002).

Further, we plot the dynamics of the gold-dollar deviation along with periods of extreme conditions in Figure 3. Six periods are identified as under the extreme regime, including those from Nov. 1981 to Jun. 1982, Feb. 1991, from Jun. to Oct. 1992, Sep. 2005, from Jun. to Nov. 2007 and from Apr. to Sep. 2008.

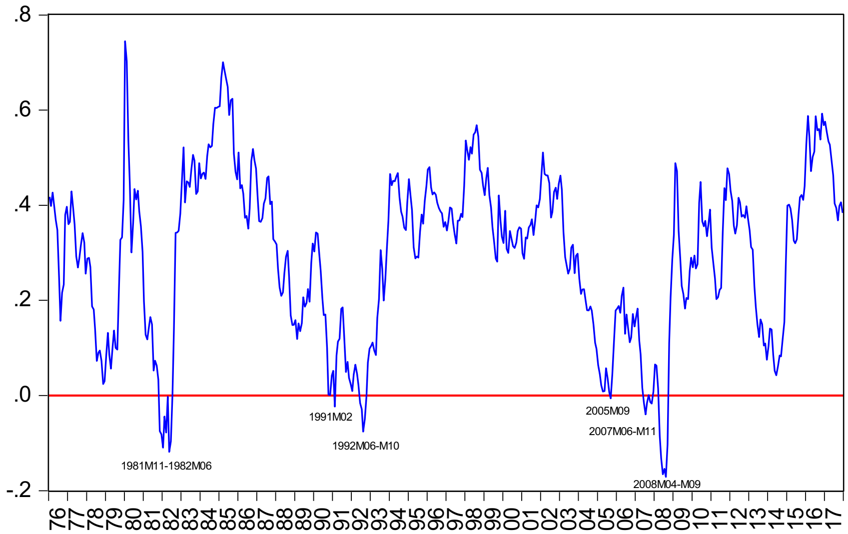

Fig. 3: The Normalized Gold-Dollar Deviation and Extreme Regime Periods

Note. This figure presents the dynamics of the gold-dollar deviation along with extreme regime periods. There are six periods that are identified as under the extreme regime, or to be specific, 1981M11-1982M06, 1991M02, 1992M06-M10, 2005M09, 2007M06-M11, and 2008M04-M09.

6 Robustness checks

6.1 The influence of financial market turmoil

A major concern is whether the threshold dynamics is truly driven by the hidden threshold process in the gold-dollar relationship, instead of coinciding with the financial market turmoil. To address this problem, we include into the model a dummy of U.S. recessions from the National Bureau of Economic Research (NBER), which has widely been used to validate economic activity indices or models (Hamilton, 1989; Issler & Vahid, 2006; Stock & Watson, 1993), and re-examine the SupLM test for the presence of a threshold. This dummy is favored since it highly correlates with the financial market turmoil and avoids arbitrary selection of crisis periods. Table 6 reports the estimation results with the recession dummy. The SupLM test statistic is 37.01 and rejects the null hypothesis at the significance level of 1%, suggesting that there is still a threshold cointegration between gold and the U.S. dollar even after accounting for the financial market turmoil. This provides empirical evidence that the threshold process does not merely coincide with extreme market conditions. Other coefficient estimates are very similar to the previous results.

And notably, the positive coefficient of the second-order lagged gold price in the dollar equation in the extreme regime is still significant.

Table 6: Estimation Results of the Threshold VECM with a dummy variable for U.S. recessions

	Typical Regime		Extreme Regime	
	Δlg_t	Δle_t	Δlg_t	Δle_t
$\mathbf{w_{t-1}}$	-0.0320**	-0.0044	-0.0967	0.0157
	(-2.39)	(-1.25)	(-0.31)	(0.13)
$\mathbf{\Delta lg_{t-1}}$	0.2198***	0.0074	-0.4109	0.0702
	(2.95)	(0.70)	(-1.48)	(0.68)
$\mathbf{\Delta lg_{t-2}}$	-0.1779**	0.0176	-0.1367	0.1871***
	(-2.53)	(1.39)	(-0.74)	(2.70)
$\mathbf{\Delta le_{t-1}}$	-0.1746	0.4025***	-0.1411	0.5288***
	(-0.94)	(9.79)	(-0.19)	(2.96)
$\mathbf{\Delta le_{t-2}}$	-0.0120	-0.0205	-0.1848	0.0846
	(-0.07)	(-0.48)	(-0.23)	(0.44)
Constant	0.5042**	0.0673	1.6032	-0.2701
	(2.37)	(1.22)	(0.33)	(-0.14)
Ir	-0.0009	0.0002*	0.0038	-0.0015
	(-1.34)	(1.82)	(1.36)	(-1.41)
M1	0.0509	-0.0301	0.4383	0.3342***
	(0.41)	(-0.99)	(1.16)	(2.90)
Stock	-0.0440	-0.0379**	0.0981	-0.1153
	(-0.60)	(-2.11)	(0.49)	(-1.45)
Ip	-0.2531	0.5011***	0.7091	0.7855***
	(-0.74)	(6.24)	(1.57)	(4.56)
Ur	0.0011	0.0001	-0.0179***	0.0052**
	(0.85)	(0.22)	(-2.77)	(2.07)
Recession	0.0066	0.0004	-0.0424***	0.0250***
	(0.56)	(0.18)	(-2.75)	(3.29)
Co. Equation	$lg_{t-1} = -3.10le_{t-1} + 15.48$			
Threshold	$lg_{t-1} + 3.10le_{t-1} > 15.48$		$lg_{t-1} + 3.10le_{t-1} \leq 15.48$	
Observations	94.41 %		5.59%	
SupLM test statistic	37.0099			
P-value	0.0004			

Note. This table reports the estimation results of the threshold VECM. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Values in parentheses are *t*-Statistics. Δlg and Δle represent the change rates of gold price and the dollar index, respectively; $\mathbf{w_{t-1}}$ is the error correction term (the gold-dollar deviation); Ir is the effective federal funds rate; M1 is the change rate of the U.S. M1 money stock; Stock is the change rate of S&P 500; Ip is the change rate of the U.S. industrial production index; and Ur is the U.S. unemployment rate. SupLM test statistic under the null hypothesis H0 of linear cointegration and P-value come from Hansen and Seo (2002). Recession is a dummy variable that equals 1 during the recession in the United States, which is highly correlated with financial market turmoil and avoids arbitrary selection.

6.2 Other exogenous variables

In addition to U.S. fundamentals, the gold-dollar relationship is also affected by other global factors (Balcilar et al., 2016; Bartsch, 2017; Sjaastad, 2008; Sjaastad & Scacciavillani, 1996). For example, Bartsch (2017) found that global economic uncertainty can move the gold return and exchange rate return volatility. Global economic cycle or the differences in economic situations are widely believed to influence the gold return or exchange rate return. Therefore, we further account for global economic uncertainty, global economic cycle, as well as differential economic situations between U.S. and other major economies. In our model, global economic uncertainty is proxied by the S&P 100 Volatility Index (VXO) from the Chicago Board Options Exchange (CBOE) [5]. The Global economic cycle is proxied by the average production of total industry in the Group of Seven. And the differences in economic situations are proxied by the 10-year Treasury constant maturity spread between the U.S. and the other countries in the Group of Seven. Table 7 reports the estimation results of the threshold VECM with these exogenous variables. The threshold progress, the long-run relationship and the short-run relationship are found once again. A 1% depreciation of the dollar corresponds to a 3.10% increase in the gold price. A mean-reverting pattern also occurs in the typical regime. The positive relationship between gold and the U.S. dollar in the extreme regime is still found.

[5] The official price history of VXO goes back to 1986. Data before 1986 are from Bloom (2009).

Table 7: Estimation Results of the Threshold VECM with other exogenous variables

	Typical Regime		Extreme Regime	
	Δlg_t	Δle_t	Δlg_t	Δle_t
$\mathbf{w_{t-1}}$	-0.0320**	-0.0073*	-0.0190	-0.0321
	(-2.40)	(-1.94)	(-0.08)	(-0.30)
$\mathbf{\Delta lg_{t-1}}$	0.2137***	0.0100	-0.3636	0.0244
	(2.80)	(0.95)	(-1.49)	(0.29)
$\mathbf{\Delta lg_{t-2}}$	-0.1831***	0.0208	-0.0304	0.1122**
	(-2.66)	(1.56)	(-0.17)	(2.03)
$\mathbf{\Delta le_{t-1}}$	-0.2285	0.3999***	0.6426	-0.0456
	(-1.24)	(9.81)	(0.66)	(-0.18)
$\mathbf{\Delta le_{t-2}}$	0.0045	-0.0174	-0.2469	0.1602
	(0.03)	(-0.41)	(-0.29)	(1.03)
Constant	0.4322**	0.1388*	-0.9062	1.7706
	(2.10)	(1.78)	(-0.19)	(0.85)
Ir	-0.0006	0.0002	0.0118	-0.0085***
	(-0.77)	(0.86)	(0.88)	(-2.80)
M1	0.0662	-0.0264	0.6452	0.1490
	(0.56)	(-0.90)	(1.08)	(1.08)
Stock	0.0220	-0.0399**	-0.3630	0.2029*
	(0.29)	(-2.21)	(-0.90)	(1.86)
Ip	-0.2441	0.4932***	0.6154	0.8343***
	(-0.72)	(6.66)	(1.33)	(5.64)
Ur	0.0004	0.0004	-0.0142	-0.0024
	(0.27)	(0.96)	(-0.63)	(-0.25)
VXO	0.0220	0.0002	-0.1046*	0.0705***
	(1.43)	(0.11)	(-1.80)	(4.91)
PTI	0.0162**	-0.0060	0.3363	-0.3098**
	(1.98)	(-0.80)	(0.71)	(-2.56)
US-G6	-0.2789	0.0022***	-0.0210	0.0177***
	(-1.07)	(3.05)	(-0.72)	(2.61)
Co. Equation	$lg_{t-1} = -3.10le_{t-1} + 15.32$			
Threshold	$lg_{t-1} + 3.05le_{t-1} > 15.32$		$lg_{t-1} + 3.05le_{t-1} \leq 15.32$	
Observations	94.41 %		5.79%	
SupLM test statistic	53.622			
P-value	0.0000			

Note. This table reports the estimation results of the threshold VECM. ***, ** and * indicate significance at the 1%, 5% and 10%

levels, respectively. Values in parentheses are *t*-Statistics. Δlg and Δle represent the change rates of gold price and the dollar index, respectively; w_{t-1} is the error correction term (the gold-dollar deviation); Ir is the effective federal funds rate; M1 is the change rate of the U.S. M1 money stock; Stock is the change rate of S&P 500; Ip is the change rate of the U.S. industrial production index; and Ur is the U.S. unemployment rate. SupLM test statistic under the null hypothesis H0 of linear cointegration and P-value come from Hansen and Seo (2002). VXO is the Chicago Board Options Exchange Market S&P 100 Volatility. PTI is the average production index of total industry in the Group of Seven. US-G6 is the 10-year Treasury constant maturity spread between the US and the other countries in the Group of Seven.

We also use the 10-year Treasury constant maturity spread between the US and Germany to proxy the differences in the economic situation[6]. The results shown in table 8 are similar to those in the original threshold VECM. This demonstrates the robustness of the results, especially the positive relationship between gold and the dollar in the extreme regime.

[6] We also use the 10-year Treasury constant maturity spread between the US and the UK, and obtain the similar results.

Table 8: Estimation Results of the Threshold VECM with interest spread between the US and Germany

	Typical Regime		Extreme Regime	
	Δlg_t	Δle_t	Δlg_t	Δle_t
$\mathbf{w_{t-1}}$	-0.0447***	-0.0064	-0.0176	-0.0485
	(-2.85)	(-1.64)	(-0.06)	(-0.42)
$\mathbf{\Delta lg_{t-1}}$	0.2193***	0.0077	-0.4444*	0.0563
	(2.86)	(0.74)	(-1.73)	(0.64)
$\mathbf{\Delta lg_{t-2}}$	-0.1723***	0.0195	-0.0584	0.1232*
	(-2.59)	(1.55)	(-0.3)	(1.84)
$\mathbf{\Delta le_{t-1}}$	-0.1637	0.4040***	0.5433	0.0621
	(-0.88)	(9.96)	(0.56)	(0.25)
$\mathbf{\Delta le_{t-2}}$	0.0129	-0.0206	-0.4853	0.1785
	(0.08)	(-0.48)	(-0.58)	(1.06)
Constant	0.9333***	0.0620	-0.1655	1.4348
	(3.11)	(0.89)	(-0.04)	(0.70)
Ir	-0.0026**	0.0002	0.0098	-0.0069**
	(-2.18)	(0.76)	(0.63)	(-2.08)
M1	0.0248	-0.0331	0.5578	0.1707
	(0.21)	(-1.12)	(0.89)	(1.14)
Stock	-0.0178	-0.0389**	-0.3650	0.1773
	(-0.24)	(-2.15)	(-0.83)	(1.42)
Ip	-0.3910	0.5049***	0.7392	0.8184***
	(-1.24)	(6.74)	(1.37)	(4.96)
Ur	-0.0013	0.0003	-0.0132	-0.0030
	(-0.77)	(0.72)	(-0.58)	(-0.33)
VXO	0.0095	0.0007	-0.0976	0.0659***
	(1.59)	(0.39)	(-1.43)	(4.01)
PTI	-0.0537**	0.0069	0.1655	-0.1820*
	(-2.07)	(1.26)	(0.49)	(-1.95)
US-Germany	0.0009	0.0013**	-0.0106	0.0083*
	(0.47)	(2.37)	(-0.52)	(1.79)
Co. Equation	$lg_{t-1} = -3.05le_{t-1} + 15.32$			
Threshold	$lg_{t-1} + 3.05le_{t-1} > 15.32$		$lg_{t-1} + 3.05le_{t-1} \leq 15.32$	
Observations	94.41 %		5.59%	
SupLM test statistic	51.9901			
P-value	0.0000			

Note. This table reports the estimation results of the threshold VECM. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Values in parentheses are t-Statistics. Δlg and Δle represent the change rates of gold price and the dollar index, respectively; w_{t-1} is the error correction term (the gold-dollar deviation); Ir is the effective federal funds rate; M1 is the change rate of the U.S. M1 money stock; Stock is the change rate of S&P 500; Ip is the change rate of the U.S. industrial production index; and Ur is the U.S. unemployment rate. SupLM test statistic under the null hypothesis H0 of linear cointegration and P-value come from Hansen and Seo (2002). VXO is the Chicago Board Options Exchange Market S&P 100 Volatility. PTI is the average production index of total industry in the Group of Seven. US-Germany is the 10-year Treasury constant maturity spread between the US and Germany.

7 Conclusion

This paper examines the nonlinear gold-dollar dynamics with a threshold vector error correction model. Empirical results confirm the presence of a threshold, suggesting divergent gold-dollar dynamics across tranquil and turmoil market conditions. Our finding is indicative of gold's role as an exchange rate hedge and portfolio diversifier. We resolve the gold-dollar puzzle of the in-tandem movement observed in the market and the usually inverse relationship grounded on economic theories. A positive correlation could occur as a result of discontinuous adjustments to the gold-dollar long-run equilibrium. Thus, the hedging role of gold is influenced by the gold-dollar threshold process. Gold's hedging role is preserved in the typical regime, but it is likely undermined due to turbulent movements and deviation from the equilibrium in the extreme regime. Our findings answer the question of when gold can be a good hedge against dollar exchange rates and when it cannot. Moreover, our work characterizes the gold-dollar relationship under extreme market conditions, showing it to be transitional across regimes. Thus, we resolve the apparent dissidence in terms of gold's safe-haven property in current literature.

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