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The Contemporaneous Link Between Gold Price and its Implied Volatility Across Market-States, Frequencies and Time Periods

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Abstract

The present work investigates quantile coherency between the price of gold and the implied volatility index (GVZ) of gold, in the US, from 2015 to 2024. The empirical results suggest: First, on average, gold traders are concerned more with sudden price upswings than with downswings. Second, the intensity and the sign of the link between gold price returns and GVZ returns depends on the market-state and the traders' time horizon. Gold price and implied volatility returns exhibit a stronger link at the upper than at the lower part of their joint distribution and the absolute magnitude of quantile coherency tends to increase (almost) monotonically from the high- to the low-frequency. Third, gold traders' perceptions regarding changes in future prices and, consequently, about self-protection, are quite volatile; Lastly, crises such as the coronavirus pandemic and the Russo-Ukrainian conflict are associated with an increase in quantile coherency.

JEL Classification: G12, C1
Keywords: Gold price**,** implied volatility, quantiles, frequencies, asymmetry

1. Introduction

Price movements and their relationship with changes in implied volatility are of paramount significance to financial market participants as it affects investment decisions, portfolio assessment, hedging, and asset and option pricing. At the same time, it is of keen theoretical interest to research economies due to the existence of competing hypotheses about the strength and the mode of it (i.e., contemporaneous *vs* lag-lead, positive *vs* negative, and symmetric *vs* asymmetric).

The price of gold is determined by the value of the US dollar, the interest rate, the demand for jewelry and industrial applications, the demand for Exchange Traded Funds (ETFs), and geopolitical tensions. Given that in international markets gold is denominated in $, the devaluation of the USD works, *ceteris paribus*, towards higher gold prices. Depending on the prevailing economic conditions, the interest rates may have a positive or negative influence on gold price. In particular, when a rising interest rate is associated with a strong economy and a bullish market sentiment, the demand for other assets may increase and the demand for precious metals may decrease. In contrast, poor consumer confidence and/or weak job reports may serve as a signal to investors to stay away from risky assets even in a high-interest rate environment. Also, gold price, *ceteris paribus*, moves in the same direction as geopolitical tensions, the demand for industrial applications, jewelry, and gold ETFs.

For equity markets, the relevant empirical literature is very big[1]. It overwhelmingly suggests that implied volatility and price returns move together, their dependence is negative, and possibly non-symmetric. Much less attention has been paid to commodities futures markets. Commodities are financial instruments with their own special supply and demand characteristics. Furthermore, unlike in equity markets, price reductions in commodities futures markets may be actually good news for a part of traders. Therefore, in commodity futures markets, the price-implied volatility relationship may be different from that in equity markets (e.g., Daigler *et al*., 2014; Fassas and Siriopoulos, 2021).

Pandungsaksawasdi and Daigler (2014) assessed the contemporaneous co-movement between crude oil, the euro, and gold price returns and their respective implied volatility indices returns in the US, using linear regression models. They found negative links for crude oil and the euro and a positive for gold. Daigler *et al*. (2014) used parametric quantile regressions to examine the contemporaneous linkage "implied volatility returns of the euro – price" in the US. According to their results, negative returns had a negative impact. On the other hand, the impact of positive returns was quantile (upper/lower) dependent. Agbeyegbe (2015) focused on the futures market for crude oil in the US, using copula quantile regressions. He reported a negative contemporaneous link that tended to be stronger at the extremes of implied volatility returns distribution. Fassas and Siriopoulos (2021) investigated the futures markets for crude oil, the euro, gold, and silver in the US, using parametric quantile regressions. For crude oil and the euro, the contemporaneous link turned out to be negative everywhere except at the 95% quantile. The relationship for the metals of silver and gold was positive under positive changes and negative under negative changes. Finally, Fousekis (2023a) examined the futures markets for crude oil, the euro, and gold in the US, using the Local Gaussian Correlation approach. For crude oil, contemporaneous co-movement was negative (almost) everywhere across the joint distribution of price and implied volatility returns; for the euro, it was positive only at the upper extremes; for gold, it was negative (positive) under negative (positive) returns regardless of changes in the implied volatility returns[2].

Relative to other commodities, gold has certain distinct features. It serves as a store of value, it is a safe-haven asset, and its market is very liquid (gold can be easily bought and sold even when conditions in other asset markets are difficult). Also, it appears to be the only commodity for which earlier studies (Pandungsaksawasdi and Daigler, 2014; and Fousekis, 2023a) pointed to a positive global (i.e., across the entire joint distribution) contemporaneous association between price and implied volatility returns. These empirical findings contrast sharply with the predictions of Behavioral Finance according to which, because traders' decisions are influenced by affect and extrapolation biases and representative heuristics, the contemporaneous link between price and implied volatility returns is likely to be negative (e.g. Hibbert *et al*., 2008).

Quantile-dependence is an important source of non-linear links between financial series. It is typically attributed to the fact that certain market-states (i.e. certain combinations of values) may serve as risk reversal points (Giot, 2015). For the gold market in particular, a

[1] For extensive reviews on equity and non-equity markets see Bekiros *et al.* (2017), Echaust (2021), and Fassas and Siriopoulos (2021).

[2] Another strand of literature has focused on the lag-lead relationship between price and implied volatility returns in commodities markets. For a review, see Raggad and Bouri (2023).

combination of a strongly positive gold price return and a strongly negative implied volatility of gold return may signal to long traders that the gold market is about to change its course. Another important source of non-linearities is frequency-dependence arising from the fact that futures markets participants often function at different time-scales. Accordingly, links of unequal intensity and mode may be relevant for different time-horizons (e.g. Gallegati, 2012; Barunik and Kley, 2019).

In light of the preceding, the goal of this study is to empirically examine the linkage among the price of gold price the implied index of volatility (GVZ) returns in the US. The empirical analysis relies is based on the Quantile Coherency approach, under which two time series depend on the state of the market as well as on the frequency[3]. Assessing how the strength and the mode between gold and GVZ returns changes under different market-states (i.e., different quantiles on their joint distribution) and under different frequencies is likely to provide potentially useful insights into gold traders' perceptions regarding risk and their needs for protection.

Recent works which employed quantile coherency in Finance have been Naeem *et al*. (2020) (stock, energy, and gold markets), Jiang *et al*. (2021) (stock and currencies markets), Mensi *et al*. (2021) (gold and energy markets), Wang (2023) (stock and commodities markets), Fousekis (2023b) (commodities markets), Uddin *et al*. (2024) (bond, commodities, currencies, and equity markets) and Hanif *et al*. (2024) (oil and European stock markets). All of the earlier works considered links between asset returns in different asset markets. This is the first application of Quantile Coherency to the the association between the returns of an asset and its implied volatility index.

The structure of the study is: the analytical framework is presented in section 2. Section 3 presents the data and the empirical model. The empirical findings from both static (full-sample) and dynamic (rolling-windows) analysis are presented in section 4 and section 5 offers conclusions.

2. Analytical framework

Consider two-variate stationary stochastic process $X_t = (X_{1t}, X_{2t})$, where $t = 1, 2, \dots T$. Consider also $\omega \in R_+$ be a frequency (time-scale) and $q_1(\tau_1)$ and $q_2(\tau_2)$ (with τ_1, $\tau_2 \in (0,1)$) be the τ_1 and τ_2 the quantiles of X_{1t} and X_{2t}, respectively. The coherency between X_{1t} and X_{2t} at frequency ω and quantiles τ_1 and τ_2 (i.e., the Quantile Coherency, denoted by $\Re$) is defined as

$$\Re = \frac{f^{1,2}(\omega; \tau_1, \tau_2)}{\sqrt{f^{1,1}(\omega; \tau_1, \tau_2) f^{2,2}(\omega; \tau_1, \tau_2)}} \tag{1}$$

(Baumohl, 2019; Barunik and Kley, 2019). In (1), $f^{j,j}(\omega;\ \tau_1, \tau_2)$ and $f^{1,2}(\omega;\ \tau_1, \tau_2)$ are the quantile spectral densities of the stochastic process X_{jt} (with j=1,2) and their quantile cross-spectral density, respectively.

[3] The standard quantile regression model associates non-linearities with the level of the dependent variable only. The local Gaussian correlation, utilized by Fousekis (2023a), obtains Pearson's correlation under different market-states. However, it is not suitable to assessing how the correlation changes with traders' time horizons. Neither the quantile regression not the local Gaussian correlation allow for frequency-dependence.

The quantile cross-spectral density (and similarly the spectral density) may be calculated as:

$$G^{1,2}_{T,R}(\omega;\ \tau_1,\tau_2) = \frac{1}{2\pi T} d^1_{T,R}(\omega,\tau_1) d^2_{T,R}(\omega,\tau_2) \tag{2}$$

where

$$d^j_{T,R}(\omega,\tau) = \sum_{i=0}^{T-1} I\{\hat{F}_{n,j}(X_{jt}) \le \tau\} e^{-i\omega t} \tag{3}$$

is the rank-based cross-periodogram and $I\{A\}$ is the standard indicator function for the event A (Barunik and Kley, 2019; Khalfaoui *et al.*, 2021). However, in order $G^{1,2}_{T,R}$ to become a consistent estimator of $f^{1,2}$, it needs to be smoothed across frequencies (Kley, 2016). The consistent estimator of quantile cross-spectral density (and similarly of the spectral density) is

$$\hat{G}^{1,2}_{T,R} = \frac{2\pi}{T} \sum_{s=1}^{T-1} W_T(\omega - \frac{2\pi s}{T})\, I^{1,2}_{T,R}(\frac{2\pi s}{T}, \tau_1, \tau_2) \tag{4}$$

where W_T is a sequence of weighted functions. Then, the consistent estimator of $\Re$ is

$$\hat{\Re}^{1,2}_{T,R}(\omega;\tau_1,\tau_2) = \frac{\hat{G}^{1,2}_{T,R}(\omega;\tau_1,\tau_2)}{\sqrt{\hat{G}^{1,1}_{T,R}(\omega;\tau_1,\tau_2)\hat{G}^{2,2}_{T,R}(\omega;\tau_1,\tau_2)}} \tag{5}$$

(Barunik and Kley, 2019).

As noted in the Introduction, quantile coherency quantifies links between stochastic processes at different parts of their joint distribution and at different time-scales. With regard to the former (i.e., the dependence of links on the market-states) it is similar in spirit to the non-parametric copulas (Patton, 2013) and the local Gaussian correlation (Tjostheim and Hufthammer, 2013) whereas with regard to the latter (i.e., the dependence of links on frequencies) it is similar in spirit to the wavelets (Gallegati, 2012) and the frequency connectedness (Barunic and Krehlic, 2018). By accounting simultaneously for two important sources of non-linearities, it offers a very detailed characterization of the association between financial or economic time series.

Quantile coherency permits conducting symmetry tests across quantile pairs (for a given frequency) as well as across time-scales (for a given quantile pair). In particular, the null hypothesis that quantile coherency is not affected by an interchange of quantiles is $\Re^{1,2}(\omega;\tau_1,\tau_2) = \Re^{1,2}(\omega;\tau_2,\tau_1)$; the null hypothesis that coherency remains the same at the lower tail, the median, and the upper tail of the joint distribution of X_{1t} and X_{2t} (i.e. radial symmetry) is $\Re^{1,2}(\omega;\tau,\tau) = \Re^{1,2}(\omega;0.5,0.5) = \Re^{1,2}(\omega;1-\tau,1-\tau)$, where τ is a small (e.g., equal to 0.05) number; The hypothesis that coherency does not change across frequencies is $\Re^{1,2}(\omega_1;\tau_1,\tau_2) = \Re^{1,2}(\omega_2;\tau_1,\tau_2) = \Re^{1,2}(\omega_3;\tau_1,\tau_2)$, where $\omega_1 > \omega_2 > \omega_3$ (Tjostheim and Hufthammer, 2013).

3. The data and the empirical model

Gold front-month futures prices ($ per ounce) and GVZ levels have been employed for the empirical part of the study. Yahoo Finance was the source of the data. The time period of the observations is between January, 1st, 2015 to September, 6th, 2024. Figure 1 presents the gold price and the GVZ level from 1/1/2015 to 6/9/2024. Initially (2015 to 2019) the price of gold fluctuated around 1200$ per ounce; from 2019 to mid-2020 it exhibited a strong upward trend; since then it has fluctuated around 1800$ per ounce. There are several local troughs and peaks. The strong decrease in late 2015 occurred against a surging USD, China's economic and stock market slump, and expectations of a higher Federal Reserve rate. The rise over the most part of 2016 occurred against geopolitical tensions (the Brexit Referendum) and a dramatic decline in stock and commodities prices. The rise in 2017 and in most of 2018 occurred against a falling USD, low interest rates, and a US stock market surge at record levels. The rise in 2018 and 2019 occurred against raging bull markets, increasing interest rates, USD appreciation, and the ongoing US-China trade war. In July 2020, gold prices reached record highs as the Covid-19 pandemic pushed the global economy into a very sharp downturn and they remained high since then against rising inflation, tight monetary policy, appreciation of the USD, banking turmoil, geopolitical tensions (e.g., the war in Ukraine and the US-China strategic competition), climate risk, and concerns about energy security. The GVZ followed a generally downward trend from 2015 to 2019 and from 2021 to the present while it has exhibited three notable peaks (in early 2016, mid-2020, and early 2022). The natural logarithms of gold prices and GVZ levels are non-stationary. Their respective first differences are stationary.[4] Accordingly, log-returns are employed for the empirical analysis. Also, given that the presence of serial autocorrelation and autoregressive conditional heteroscedasticity may lead to spurious contemporaneous association (Barunik and Kley, 2019), the filtering of the raw log-returns with the most suitable models of ARMA-GARCH has been undertaken with the goal of obtaining *i.i.d.* observations. For log-gold returns, the specification is the ARMA(3,1)-GARCH(1,1) and for log-GVZ returns, it is the ARMA(1,1)-GARCH(1,1). The two specifications turned out to be sufficient for removing autocorrelation and ARCH effects up to 24 lags.

Quantile coherency has been estimated at nine quantile pairs and at three frequencies. The quantile pairs are (0.05, 0.05), (0.05, 0.50), (0.05, 0.95), (0.5, 0.05), (0.50, 0.50), (0.95, 0.05), (0.95, 0.50), and (0.95, 0.95), where the first (second) number in each pair refers to the state of price (GVZ) returns. Market-states were also selected (Fousekis, 2023b). Frequencies are very short-run (2 futures markets days), medium-run (10 futures markets days or equivalently 15 calendar days), and longer-run (22 futures markets days or equivalently 30 calendar days). Consistency of the non-parametric estimator of quantile coherency (equation (3)) has been ensured by employing the mean squared error minimizing bandwidth $b_n = 0.5(n^{-0.25})$ as suggested by Barunik and Kley (2019).

4. The empirical results

4.1 Static (full-sample) analysis

Before presenting the empirical findings, it will be useful to examine, as a preliminary step, certain features of contemporaneous link between gold price and GVZ returns "on average" (i.e., on the aggregate across market-states, frequencies, and time periods). Table 1 presents the standard Pearson correlation coefficient (ρ) along with three maximal information-based non-parametric exploration (MINE) statistics; namely, the maximal information coefficient (MIC), the difference $\text{MIC} - \rho^2$, and the maximum asymmetry score (MAS). The ρ is a signed measure of linear association. The MIC, ranges from 0 (for independent data) to 1 (for a noiseless functional relationship). The $\text{MIC} - \rho^2$ and the MAS capture departures from linearity and monotonicity, respectively[5]. In Tables 1-7, all *p*-values are reported in

[4] The properties of the two stochastic processes have been verified using the KPPS test. The results are available upon request.
[5] For details on the construction of the MINE statistics see Reshef *et al*. (2011).

parentheses and they have been obtained using a Wald-type test (Patton, 2013) and Block Bootstrap (Politis and Romano, 1994) with 1000 replications.

Results suggest that the two stochastic processes are not independent of each other. The null hypotheses of linearity and monotonicity are rejected suggesting that the contemporaneous relationship among gold price and GVZ returns is quite complex.

The sign of the "GVZ - gold price" relationship is determined by future expectations of the traders and their actions in order to be protected. A positive sign indicates that traders are more concerned with a sudden rise than a sudden drop in price; their marginal willingness to pay for upside protection increases; consequently, the call options price that are OTM (Out-of-the Money), relatively, increases (Daigler *et al*., 2014; Pandungsaksawasdi and Daigler, 2014). Gold prices rise in economic turmoil and so does the value of GVZ (Fousekis, 2023a). Accordingly, gold can act as a safe-haven asset.

Table 2 presents coherency estimates on at the nine market-states and the three time-scales (frequencies)[6]. On the small time-scale, four estimates (at quantile pairs (0.5, 0.5), (0.5, 0.95), (0.95, 0.50), and (0.95, 0.95)) are of statistical significance below the 1% level and one estimate (at quantile pair (0.05, 0.95)) at the 6.6 per cent level or less. All five estimates are positive; the first four involve combinations where both price and GVZ returns are above their respective 0.5 quantiles; the fifth estimate involves a combination with extreme positive returns for the GVZ as well as extreme negative returns for the price of gold. From the sign and statistical significance of the estimates it appears that in the short-run: (a) In the upper segment of the distribution, the two stochastic processes are well linked; and (b) the main driver of traders' behavior is their concern about sudden gold price upswings whereas their relative demand for OTM calls and puts is largely insensitive to gold price downswings. On the medium frequency, eight estimates (at quantile pairs (0.05, 0.05), (0.05, 0.95), (0.5, 0.05), (0.5, 0.5), (0.5, 0.95), (0.95, 0.5), and (0.95, 0.95)), are of statistical significance. Three of them (at quantile pairs (0.05, 0.05) and (0.5, 0.05), and (0.95, 0.05)) are negative and the rest are positive. All three negative involve combinations with extreme negative GVZ returns; with just one exception (the pair (0.05, 0.95)) the positive estimates involve combinations where both price and GVZ returns above their respective 0.5 quantiles. The negative sign (at quantile pairs (0.05, 0.05) and (0.5, 0.05), and (0.95, 0.05)) suggests that deceleration of fear (or equivalently a euphoric market sentiment) may lead investors to switch from gold to riskier assets placing, thus, downward pressure on the gold price. The positive sign of the remaining statistically significant estimates implies that, as for the short-run, gold traders are more concerned about sudden drops in prices. On the large time-scale, eight estimates (which involve exactly the same market-states as the medium-frequency) are of statistical significance.

Comparing the absolute values of the estimates for the same market-state across the three frequencies one observes that they tend to acquire higher values as the scale of the time increases[7]. The only exception is coherency at the median of the joint distribution; it is sizable and statistically significant at the high-frequency but very small and statistically insignificant at the medium- and at the low-frequency. This, in turn, implies that the effect of moderate shocks to both gold price and the GVZ have a very short-lived impact on traders'

[6] The package Quantspec in R has been utilized for the empirical analysis (Kley, 2016).

[7] For completeness, quantile coherency has been also estimated with a time-scale equal to 66 stock market days (or equivalently 90 calendar days). The estimates turned out to be almost the same as those with the time-scale equal to 22 (the biggest difference was 0.011 and occurred at the quantile pair (0.95, 0.50). This is a strong indication that the effect of shocks to gold prices and/or to GVZ levels on traders' perceptions might not exceed the time period of one month in order to be completed.

risk perceptions. It is also interesting that coherency at the lowest extreme (0.05, 0.05) is statistically significant at the medium- and the low-frequency pointing to the presence of links (although of opposite sign) on both tails of distribution.

The Finance literature distinguishes between fundamental-based and pure contagion (Bodart and Candelon, 2009). The former refers to the presence of strong links across all market-states and time-scales whereas the latter to the presence of strong links only at the high-frequency (due to traders' panic and herding behavior). Here, the link between gold returns and volume is somehow weak in the small time-scale but increases substantially in the medium- and the longer-run. One, therefore, may conclude that the relationship between gold returns and the GVZ is primarily driven by fundamental-based contagion.

Table 3 (panel (a)) presents the test results on radial symmetry for time-horizons that are small. The null hypothesis that coherency is the same at the low extreme, the median, and at the upper extremes of the joint distribution is rejected at the level of 1% and below of it. In addition, the null hypothesis that coherencies at the low and the upper extremes are not different one from the other is also rejected at the level of 1% and below of it. In panel "b" of Table 3, the study presents the findings on exchange symmetry tests for the small time-scale. The null of equality is rejected for the quantile pairs (0.05, 0.95) and (0.95, 0.05). Table 4 presents the findings on radial (panel (a)) as well as on exchange symmetry (panel (b)), for the medium time-scale. These are qualitatively the same as for the high-frequency. Table 5 (panels (a) and (b)) shows the test results on radial and exchange symmetry, respectively, for the large time-scale. The only qualitative difference relative to the other two frequencies is that the null hypothesis of exchange symmetry is now rejected for the quantile pairs (0.5, 0.05) and (0.05, 0.5) as well.

Tests for symmetry across high frequencies, medium frequencies and low-frequencies are exhibited in Table 6. For the pairs (0.5, 0.05), (0.5, 0.5), and (0.05, 0.95), we reject the null hypotheses of equality. Given that (from Table 1) the differences in magnitude between the estimates on the large and the medium time-scales are small, the rejections are mainly driven by the increase (in the absolute value) of coherency from the high-frequency to the medium-frequency. Table 7 presents the findings for tests on symmetry at the low- and at the high-frequencies only. For two market-states ((0.5, 0.05) and (0.5, 0.5)) the relevant null hypotheses are rejected. Overall, the tests results suggest that asymmetric links (including reversals of risk perceptions) have higher probability in occurring across different segments of the joint distribution of the same frequency than at the same market-state across frequencies.

4.2 Dynamic analysis

For the dynamic analysis, the length of the rolling window is equal to two-hundred and fifty (250) futures market days. Figure 2 presents the evolution of coherency for each market-state in the three time-scales. For all 9 market-states considered, quantile coherency exhibited very large volatility both due to changes in its absolute magnitude and its sign. In very few cases (most notably, for the pair (0.50, 0.50)) coherency on the three time-scales generally had the same direction. For the majority of market-states, however, an increase (decrease) in coherency at the low- and at the medium- frequencies was very often associated with a decrease (an increase) in coherency at the high-frequency; the most notable example is the quantile pair (0.5, 0.05). That type of behavior reinforces the evidence from the static analysis that traders' risk perceptions have been similar at the medium and the large time-scales and different from those at the small time-scale.

As noted in Section 3, several factors determine the price of gold and the level of GVZ. Some (or even all of them) may be relevant in a given sub-period; therefore, a detailed explanation of the evolution of quantile coherency for every market-state and frequency is not easy. Nevertheless, some observations can still be made. For most quantile pairs, coherencies exhibited a peak in windows ending in mid-2020. These, typically involved only the medium- and the large time-scales and less often all frequencies. To a large extent, the same observation holds in windows ending in mid-2022, and in late-2017 and early-2018. The peaks in mid-2020 and mid-2022 occurred during the coronavirus pandemic and during the Russo-Ukrainian conflict; in late-2017 and in early-2018, the peak occurred with strong economic growth, low interest rates, and a weak USD. It appears that in all these sub-periods traders were primarily concerned with possible sudden gold price increases. For most quantile pairs, coherencies (especially those at the medium and large time-scales) exhibited a trough for windows ending in early-2019 and in late-2021. In 2018, both the USD and the interest rate were on the rise whereas in 2021 the USD was falling and the interest rate was close to zero. It appears that in all these sub-periods traders were primarily concerned with possible sudden gold price decreases.

5. Conclusions

The goal of this study has been to examine the intensity and the

pattern of the contemporaneous link between the returns of the price of gold and the GVZ returns with the utilization of quantile coherency. Findings sugest:

(a) Gold price returns and GVZ returns are not independent of each other; they maintain a non-linear and non-monotonic relationship. On average (that is, on the aggregate across all frequencies, market-states, and time periods) the link is positive suggesting that traders in the futures markets for gold are concerned more with sudden price upswings than with downswings.
(b) Coherency is weak at the small time-scale but it increases (almost) monotonically with the time horizon considered. However, the impact of shocks to gold prices or to the GVZ levels on investors' concerns and preferences is likely to be completed within 22 futures markets days.
(c) Both the absolute magnitude and the sign of coherency vary across market-states for the same frequency. The strength of the link is more intense at the upper extreme relative to the lower extreme. Risk reversals (negative coherency instead of positive) typically occur at market-states involving extreme negative GVZ returns.
(d) The evidence of asymmetric coherency is more pronounced across market-states for the same frequency than across frequencies for the same market- state. It appears that, given a market-state, the time horizon on which traders operate has a moderate influence on their perceptions about whether they should seek protection against rising or falling gold prices.
(e) Quantile coherency between gold price and GVZ returns (regardless of market-state or frequency) exhibits considerable volatility over time suggesting that investors' perceived risks, needs, and preferences change very often.

The empirical findings here have three important implications for investors. First, because gold price returns and GVZ returns depend on each other, the price of gold and its options have a close relationship. Secondly, given that market-states have considerable influence on both the intensity and the pattern of coherency, investors should take market-states into account when deciding about their needs for protection. Third, because coherency is asymmetric, knowledge of the absolute magnitude and the sign of the association at a given quantile pair (and/or on a given frequency) cannot be, generally, used to form expectations about coherency at different market- states and/or time-scales.

As mentioned in the Introduction, this is the first work that has investigated relationship between the returns of an asset and its implied volatility using the Quantile Coherency approach. Gold has distinct characteristics relative to other assets. Therefore, it would be unwise to claim that the empirical findings here are relevant to other cases (e.g., the link between the stock market index S&P500 and its implied volatility index (VIX) or the relationship between crude oil and its implied volatility index (OVX). Given the theoretical and practical importance of the topic, additional research is certainly warranted.

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Appendix

Figure 1. Gold price and its implied volatility index (GVZ) level

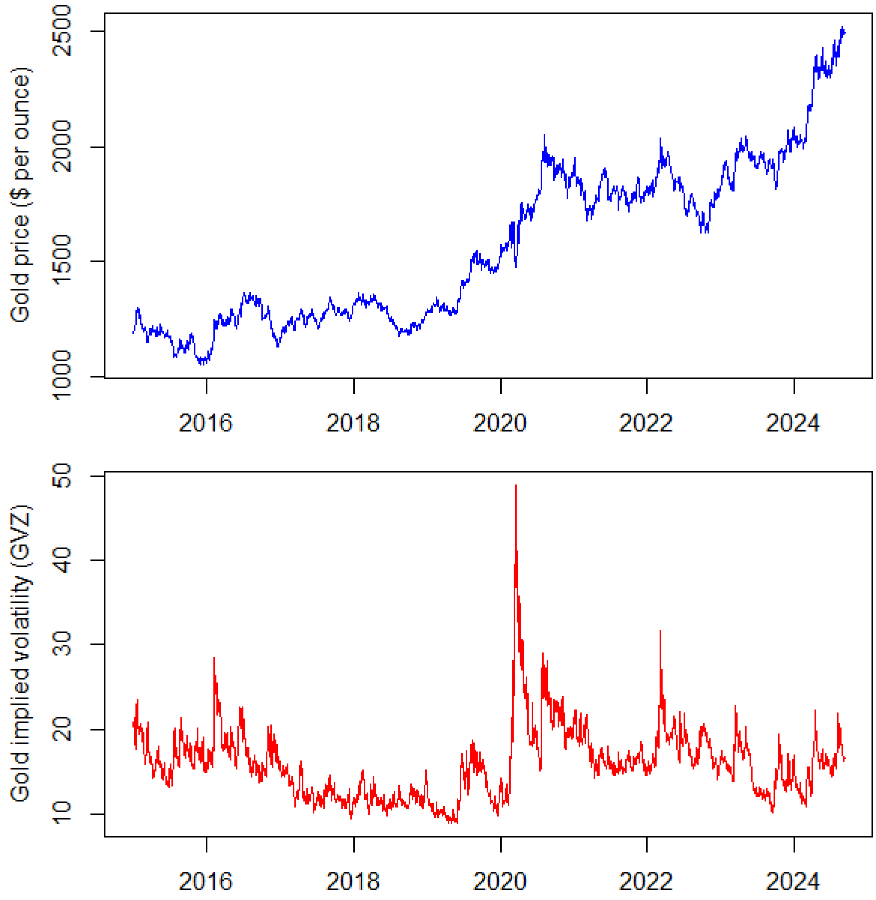

Figure 2. Dynamic analysis.
The evolution of quantile coherencies

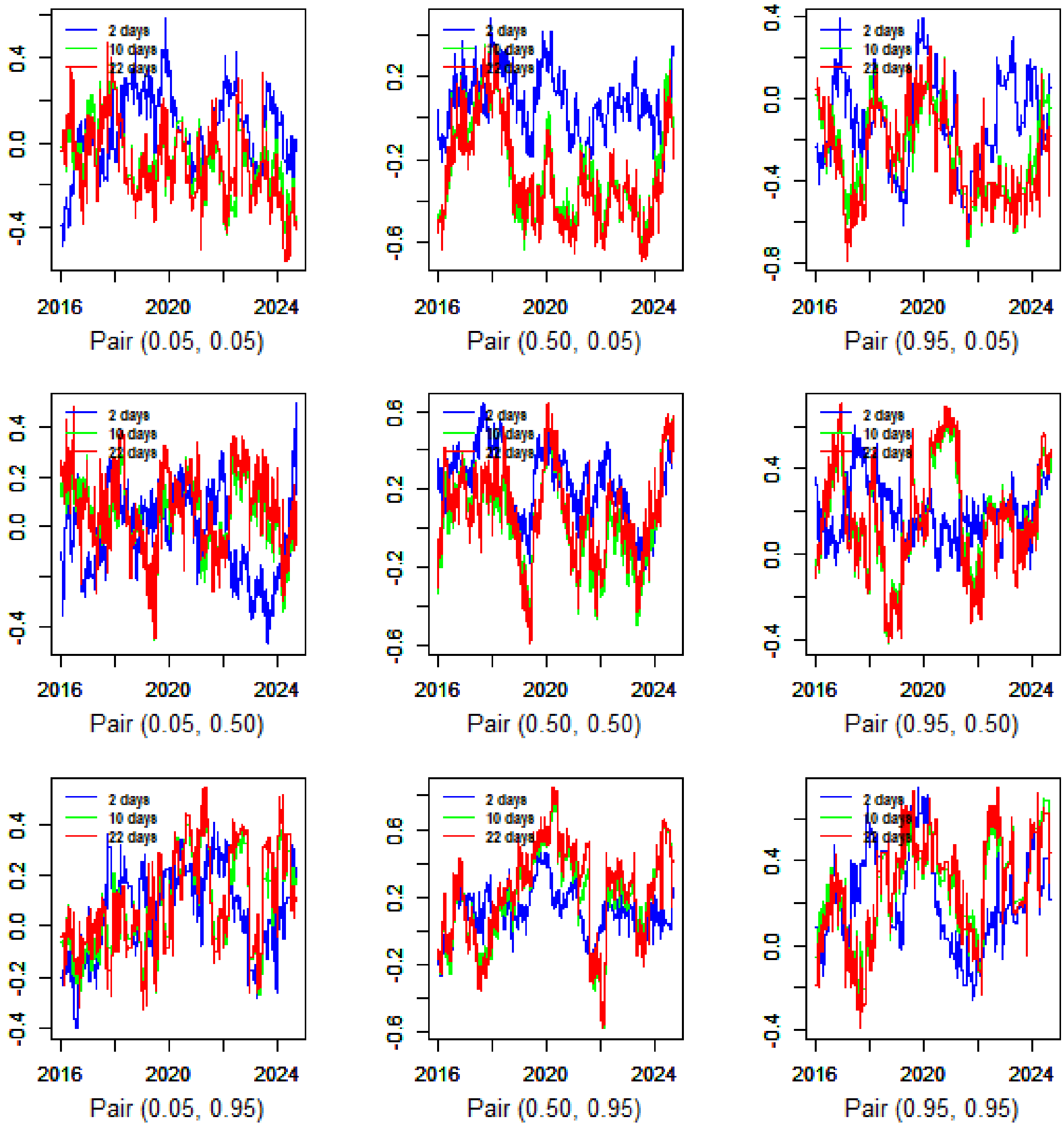

Table 1. Global measures of association and tests on independence, linearity, and monotonicity

ρ	MIC	MIC- ρ^2	MAS
0.141 (<0.01)	0.152 (<0.01)	0.132 (<0.01)	0.05 (<0.01)

Table 2. Static analysis.
Coherency estimates across market-states and time-scales

		Time-scale		
Quantile pair (market-state)		2 days	10 days	22 days
Gold price returns	GVZ returns			
0.05	0.05	-0.049	-0.155	-0.186
0.05	0.5	(0.355) 0.019 (0.744)	(0.014) 0.109 (0.078)	(0.011) 0.134 (0.054)
0.05	0.95	0.095	0.176	0.217
0.5	0.05	(0.066) 0.044	(<0.01) -0.226	(<0.01) -0.261
0.5	0.5	(0.471) 0.261 (<0.01)	(<0.01) 0.029 (0.657)	(<0.01) 0.057 (0.439)
0.5	0.95	0.157 (<0.01)	0.164 (0.021)	0.179 (0.03)
0.95	0.05	-0.099	-0.244	-0.275
0.95	0.5	(0.144) 0.20 (<0.01)	(<0.01) 0.203 (<0.01)	(<0.01) 0.207 (<0.01)
0.95	0.95	0.256 (<0.01)	0.326 (<0.01)	0.326 (<0.01)

Table 3. Static analysis.
Symmetry tests
(time-scale: 2 days)

(a) Radial symmetry

Ho: coherency is equal at the quantile pairs	Test statistics
(0.05,0.05), (0.5,0.5), and (0.95,0.95)	-0.311 and -0.055
	(<0.01)
(0.05,0.05) and (0.95,0.95)	-0.305
	(<0.01)

Notes: For the test that involves coefficients, the test statistics are coherency on market-state in the first parenthesis minus coherency on market-state in the second parenthesis and coherency on market-state in the second parenthesis minus coherency on market-state in the third parenthesis.

(b) Exchange symmetry

Ho: coherency is equal at the quantile pairs	Test statistic
(0.05,0.5) and (0.5,0.05)	-0.025
	(0.75)
(0.05,0.95) and (0.95,0.05)	0.195
	(0.023)
(0.5,0.95) and (0.95,0.5)	-0.042
	(0.552)

Notes: (a) The first (second) number in parentheses under the Ho is the quantile for gold price (GVZ) returns where coherency is estimated. (b) The test statistic is coherency on market-state in the first parenthesis minus coherency on market-state in the second parenthesis.

Table 4. Static analysis.
Symmetry tests
(time-scale: 10 days)

(a) Radial symmetry

Ho: coherency is equal at the quantile pairs	Test statistics
(0.05,0.05), (0.5,0.5), and (0.95,0.95)	-0.185 and -0.296 (<0.01)
(0.05,0.05) and (0.95,0.95)	-0.482 (<0.01)

Notes: For the test that involves coefficients, the test statistics are coherency at market-state in the first parenthesis minus coherency at market-state in the second parenthesis and coherency at market-state in the second parenthesis minus coherency at market-state in the third parenthesis.

(b) Exchange symmetry

Ho: coherency is equal at the quantile pairs	Test statistic
(0.05,0.5) and (0.5,0.05)	0.344 (<0.01)
(0.05,0.95) and (0.95,0.05)	0.42 (<0.01)
(0.5,0.95) and (0.95,0.5)	-0.039 (0.567)

Notes: (a) The first (second) number in parentheses under the Ho is the quantile for gold price (GVZ) returns where coherency is estimated. (b) The test statistic is coherency at market-state in the first parenthesis minus coherency at market-state in the second parenthesis.

Table 5. Static analysis.
Symmetry tests
(time-scale: 22 days)

(a) Radial symmetry

Ho: coherency is equal at the quantile pairs	Test statistics
(0.05,0.05), (0.5,0.5), and (0.95,0.95)	-0.243 and -0.269 (<0.01)
(0.05,0.05) and (0.95,0.95)	-0.512 (<0.01)

Notes: For the test that involves coefficients, the test statistics are coherency at market-state in the first parenthesis minus coherency at market-state in the second parenthesis and coherency at market-state in the second parenthesis minus coherency at market-state in the third parenthesis.

(b) Exchange symmetry

Ho: coherency is equal at the quantile pairs	Test statistic
(0.05,0.5) and (0.5,0.05)	0.395 (<0.01)
(0.05,0.95) and (0.95,0.05)	0.492 (<0.01)

Notes: (a) The first (second) number in parentheses under the Ho is the quantile for gold price (GVZ) returns where coherency is estimated. (b) The test statistic is coherency at market-state in the first parenthesis minus coherency at market-state in the second parenthesis.

Table 6. Static analysis.
Symmetry tests
(across all three frequencies)

Ho: coherency is equal across the three frequencies at the quantile pairs	Test statistics	Ho: coherency is equal across the three frequencies at the quantile pairs	Test statistics
(0.05,0.05)	0.106 and 0.03 (0.207)	(0.95,0.5)	-0.004 and -0.003 (0.981)
(0.5,0.05)	0.269 and 0.035 (<0.01)	(0.05,0.95)	-0.081 and -0.04 (0.06)
(0.95,0.05)	0.145 and 0.031 (0.121)	(0.5,0.95)	-0.006 and -0.002 (0.699)
(0.05,0.5)	-0.09 and -0.025 (0.309)	(0.95,0.95)	-0.07 and -0.0003 (0.691)
(0.5, 0.5)	0.232 and -0.028 (<0.01)		

Notes: (a) The first (second) number in parentheses under the Ho is the quantile for gold price (GVZ) returns where coherency is estimated. (b) The statistics are coherency in 2 days minus coherency in 10 days and coherency in 10 days minus coherency in 22 days.

Table 7. Static analysis.
Symmetry tests
(2 *vs* 22 stock market days)

Ho: coherency is equal in large- and small- frequency at the quantile pairs	Test statistic	Ho: coherency is equal in large- and small- frequency at the quantile pairs	Test statistic
(0.05,0.05)	0.136 (0.13)	(0.95,0.5)	-0.007 (0.934)
(0.5,0.05)	0.304 (<0.01)	(0.05,0.95)	-0.122 (0.149)
(0.95,0.05)	0.176 (0.063)	(0.5,0.95)	-0.022 (0.814)
(0.05,0.5)	-0.115 (0.218)	(0.95,0.95)	-0.07 (0.433)
(0.5, 0.5)	0.203 (0.028)		

Notes: The first (second) number in parentheses under the Ho is the quantile for gold price (GVZ) returns where coherency is estimated. (b) The statistics are coherency in 2 days minus coherency in 22 days.