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Zero Lower Bound Monetary Policy's Effect on Financial Asset's Correlations

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Abstract We investigate the hypothesis that zero lower bound monetary policy has an effect on the correlations of financial assets. Using an event-study approach, we evaluate the impact of the zero lower bound monetary policies of the Bank of Japan, the Bank of England, and the Federal Reserve on the bond and equity markets in Japan, the UK, the US, and the Eurozone. We evaluate the bond markets using the Japanese 10-year Sovereign bond (JGB), UK 10-year bond (Gilt), US 10-year Treasury note (T-note), and German 10-year bond (Bund). For the equity markets we use the Nikkei 225, FTSE 100, S&P 500, and Euro STOXX 600 as proxies for each regional market. We also include gold and silver as control commodities. Our analyses demonstrate significant changes not only in the evaluated assets' correlations with each other, but also in their general behavior. This has major implications for investment portfolio construction and provides useful insight for financial service regulators and the central banks themselves in monitoring the fragility and stability of the financial system.

Keywords Zero lower bound monetary policy · Financial markets · Portfolio construction

JEL Classification C10 · F30 · F39 · G10 · G15 · G20

Introduction

We investigate correlations between major asset classes in the presence of zero lower bound monetary policy (ZLB), which is when a central bank seeks to push interest rates to zero or near-zero. For our purposes, we define zero lower bound ranges, an upper and lower bound, for each of the economic regions we evaluate. These ranges are

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specified later in this paper. Monetary policy is used as a tool to help expand or contract an economy (Waud 1970). For example, in the case of the Federal Reserve such policy is often the product of a monetary policy reaction function, which is an inflation-forecast-based rule used to determine how nominal short-term interest rates should be adjusted in response to changes in the differences between observed and potential output, and between forecasted core inflation and the Fed's inflation target. A commonly used rule, or a variation of it, is the Taylor rule (Taylor 1993). In times of slow economic growth[1] newly-created money is often injected into the financial system in an effort to lower interest rates by increasing the supply of available loanable funds. These lower interest rates translate to reduced borrowing costs which ideally incentivize increased investments in wealth-producing activities, such as new business capital investments. In turn, the increased wealth-producing activities should lead to increased economic growth and employment, along with increased investments into securities markets. In Keynesian economic theory when interest rates are pushed towards zero, which is the situation this paper is concerned with, there is the possibility of a liquidity trap. A liquidity trap occurs when individuals and businesses hoard money in expectations of adverse events, such as deflation, general economic collapse, or war. The trap is created as a byproduct of this cash hoarding, which results in the desired effects of injecting new money into the financial system, the lowering of interest rates not occurring thereby rendering such a monetary policy mechanism ineffective.[2]

Unfortunately, an increase in the money supply historically is often followed by an increase in the inflation rate, often with a lag of well over a year (Friedman 1972). Rational investors take this expectation into account when choosing assets to invest in. Traditionally, investors have diversified their investments by concurrently investing in both the bond market and the equity market. In contemporary times, as the economies of the world have continued to demonstrate sluggish growth, many central banks have sought to push interest rates to or nearly to zero, and then hold them there for longer than ever before. As a result, the bond market has seen yields plummet to levels where the nominal rates of return are often less than the expected inflation rate, which in turn can lead to negative real rates of return to bondholders. This would seem to drive investors away from the bond market and quite possibly into the equity market.

Motivation

The genesis of this paper comes from a verbal conversation with an investment portfolio manager at a major hedge fund in Connecticut, USA. This portfolio manager stated, "One more pragmatic thought might be to study the impact of zero-rate monetary policy on financial asset correlations; that's an issue that keeps portfolio managers up at night." Specifically, portfolio managers are particularly interested in the changes in the correlations between any two given asset classes. Holding negatively correlated assets is a useful tool in reducing overall portfolio risk. Many portfolio managers must adhere to risk maximums as stated in their investment policy statements (IPS). Hence, assets are allocated in an effort to maintain risk within the allowed risk limits. Prior to central bank ZLB

[1] This is currently the situation in most of the industrialized world.

[2] While the extent to which this is true in the current ZLB environment would make an interesting and useful study, it is outside of the scope of this paper.

implementations, portfolio managers often held 10-year sovereign bonds as a means of reducing overall portfolio risk by offsetting equity risk. However, while portfolio managers have risk limits they must comply with, they must also simultaneously meet rate-of-return targets. Failing to meet these targets does not bode well for the portfolio or its manager.

Focus and Possible Application of Analytical Results

We investigate correlations between select major asset-classes immediately before (pre-ZLB) and then in the presence of (during) ZLB implementation. Our general approach is to evaluate changes in the correlations between a 10-year sovereign bond and a major equity index in each of four major economic regions: Japan, the UK, the US, and the Eurozone.

In this paper we investigate asset correlations over a 33 year period, from January 1980 to May 2013. Our results should be of benefit to researchers, investment analysts, medium and longer-term traders, portfolio managers, pension fund managers, and, in general, the majority of the investment community. Our results can also be useful to financial service regulators and the central banks themselves in monitoring the fragility and stability of the financial system.

Analytical Approach

We investigate four economic regions whose central-banks lowered their policy rates into the ZLB monetary realm. The central-banks in these regions have the most profound effects on their respective economic regions and on the global economy. These central banks are the Bank of Japan (BOJ), the Bank of England (BOE), the US Federal Reserve (Fed), and the European Central Bank (ECB); however, the ECB did not begin operations until January 1, 1999 and did not implement ZLB policy within the analysis time span in this paper; therefore, our treatment of the European area is limited to the effects of other central bank ZLB implementations on European securities.

We employ an event-study approach in an effort to contrast data behavior before- and during-ZLB implementation. We construct a correlation matrix using all data over the entire time span of the data sets. Next, we determine the ZLB implementation points and construct correlation matrices before and after these points (pre-ZLB and during ZLB implementation). Finally, we employ time-series analyses to test the significance of changes in the volatility, pre-ZLB and during the ZLB implementation. These time-series analyses are intended as robustness tests of and to shed additional light on the correlation analyses. The changes in volatility suggest changes in the market activity associated with the financial assets being evaluated.

Literature

While there is an abundance of academic literature concerned with monetary policy and its effects on asset prices in general and on prices in the ZLB realm, little, if any, of it directly addresses the matter investigated in this paper. Our research effort enters mostly unchartered territory focusing on changes in the correlations between major asset-classes in association with changes in monetary policy, particularly ZLB.

Some researchers argue that changes in monetary policy influence forecasts of market-determined interest rates in the short-run (Waud 1970). Roley and Troll find that the discount rate plays a significant role in the implementation of monetary policy, as evidenced when the Fed switched to a reserve-based approach of monetary control (Roley and Troll 1984). Some studies use high-frequency data and find correlations between monetary policy changes and daily or intraday stock returns in the United States (Waud 1970; Smirlock and Yawitz 1985; Cook and Hahn 1988).

Many economists say that restrictive (accommodative) monetary policy leads to lower (higher) stock prices (Jensen and Johnson 1995; Conover et al. 1999a, b). Then, pursuing a longer-run analytical horizon, Jensen and Johnson (1995) examine monthly and quarterly performance. They find that expected stock returns are significantly greater during expansive monetary periods. Conover et al. (1999a, b) make similar inferences using cross-country data.[3] However, Durham (2001, 2003) finds that Jensen and Johnson's findings are highly sensitive to alternative proxies for monetary policy.

One group of recent research finds that individual country results suggest that there are no major differences in the macroeconomic effects of unconventional monetary policies across countries (Gambacorta et al. 2012), while another research effort concludes the effectiveness of unconventional policy actions in stimulating activity are attenuated relative to conventional policy actions (Kiley 2013). Kiley also finds that attenuation of the increase in equity prices, relative to a 100 basis-point decline in 10-year Treasury yields since the beginning of 2009, does not represent a change in response to monetary-policy induced movements in interest rates; rather, it reflects the importance of both short- and long-term interest rates. Gilchrist et al. (2014) find the efficacy of unconventional policy in lowering real borrowing costs is comparable to that of conventional policy.

Other ZLB research finds that in a New Keynesian economy an increase in the variance of shocks to the discount factor process reduces consumption, inflation, and output by a substantially larger amount when the zero lower bound is binding than when it is not (Nakata 2013). Swanson and Williams (2013) investigate the efficacy of monetary policy on the overall path of short-term interest rates versus the overnight rate in the present of ZLB. They seek to address the effectiveness of monetary policy versus fiscal policy in the ZLB realm. The authors find that yields on Treasury securities with a year or more to maturity were surprisingly responsive to news throughout 2008–2010, suggesting that monetary and fiscal policy were likely to have been about as effective as usual during this period. They find that only beginning in late 2011 does the sensitivity of these yields to news fall closer to zero.

Data

International Policy Rates

The historical monetary policy rates used in this paper are from the Reserve Bank of Australia (RBA) website. This website has policy rates for the BOJ, the BOE, the Fed,

[3] Among various nations.

and the ECB, dating back to January 1980, May 1997, January 1980, and January 1999, respectively, up to May 2013. The databank from the RBA gives international policy rates in monthly form.

The BOE and ECB only have policy rates going back to May 1997 and January 1999, respectively. This is because: (1) the BOE was not granted full operational independence for monetary policy until May 6, 1997, and (2) the ECB did not exist until June 1, 1998, the date it was established in accordance with the Treaty of Maastricht. The ECB did not begin full-scale operations until January 1, 1999.

To create a continuous BOE policy rate going back to January 1989 we use the monthly UK interbank rates from January 1989 to May 1997 and use them to create a proxy continuous policy rate data set for the BOE.[4] We do not use ECB policy rates, but do include Eurozone financial assets in the analyses. This is due to insufficient ECB data. When the data for this research effort was initially collected, up to May 7, 2013, the ECB had not lowered their policy rate into the defined ZLB monetary policy realm of 0.50 percent or lower. However, on August 5, 2013 the ECB pushed the rate into the ZLB realm. That ZLB implementation is outside of our analysis window. Finally, we determine the exact monetary-policy implementation dates from the respective central bank's websites.

Bond and Equity Representatives

We use the 10-year sovereign bond yields and major equity index values in each of the four regions that the BOJ, BOE, Fed, and the ECB govern. The bonds are the Japanese 10-year bond (JGB[5]), the UK 10-year bond (Gilt), the US 10-year Treasury-note (T-note), and the German 10-year bond (Bund), respectively. The German Bund was chosen to represent the European region as it is generally regarded as Europe's safe haven for bond investments. This is evidenced by the Bund having the lowest yield of all European sovereign bonds (high price due to high demand) and increased investment in it, which is consistent with bad news announcements concerning Europe's economic situation. The equity indices are the Nikkei 225, FTSE 100, S&P 500, and the Euro STOXX 600, respectively.[6] All of these data sets were obtained using a Bloomberg terminal.

Gold and Silver

Gold and silver are monetary commodities recognized the world over and throughout written history; hence, we use gold and silver prices as benchmark commodities. While these two key metals possess many similarities, they also possess two key differences as well. Whereas gold is seen primarily as a precious metal, silver is both a precious metal and an industrial metal. Hence, silver provides an informational bridge into perceived improvements in the industrial sector, as opposed to just being a financial hedge. Further, gold and silver are real assets and are seen to have real intrinsic value,

[4] These data were acquired using the tradingeconomics.com website

[5] JGB-Japan Government Bond.

[6] Henceforth referred to simply as the Nikkei, FTSE, S&P, and STOXX.

as opposed to many other financial assets, which all-too-often constitute mere promises of value.[7] Both gold and silver prices are obtained using a Bloomberg terminal.

Zero Lower Bound Monetary Policy Ranges

The rates we use to represent ZLB are: BOE, 0.00 %–0.50 %; Fed, 0.00 %–0.50 %; and BOJ, 0.00 %–0.15 %. As previously discussed, ZLB monetary policy is defined as when a central bank seeks to push interest rates down to zero or nearly to zero. There is no universally agreed-upon numerical rate specified for exactly when rates are in the ZLB realm; hence, for our evaluation we defined it as 0.00 %–0.50 % for BOE and the Fed. This upper limit of 0.50 % is low enough to be reasonably near zero, while still allowing some movement in rates above zero in order to have a sufficiently large enough data set within the ZLB range. However, we had to set the upper rate for the BOJ lower than the other regions because the BOJ has dropped their rates to much lower levels than the other regions' central banks and they did this more frequently. The Japanese economy was not affected by low interest rates above 0.15 % like the other economic regions were in the 0.15 %–0.50 % range. This is clearly evident in the TGARCH analyses presented later in this paper. For this reason, we believe that a ZLB range of 0.00–0.50 % for Japan is too high and would place too much of the data within the ZLB range; hence, our use of a 0.00 %–0.15 % range for the BOJ.

Japan has three ZLB implementations over the time span evaluated in this paper, while the BOE and Fed each have one ZLB implementation over the same time span. The dates of the ZLB implementations are as follows: BOJ: first round, March 3, 1999; second round, March 21, 2001; and third round, December 22, 2008. BOE: March 5, 2009. Fed: December 16, 2008.

Analysis

Asset Correlations

In this section we evaluate the correlations between the selected assets using daily data. Correlation matrices are constructed for each monetary region's pre- and during central bank ZLB implementation. However, we do not accomplish correlation matrices for ECB ZLB implementation for the reasons previously discussed. These correlation matrices indicate the correlation coefficients between the 10-year sovereign bonds, equity indices, gold, and silver, under each monetary regime. In the interest of brevity these matrices are not included in this paper. They are available upon request.

Summaries of the correlations between the different asset-classes are presented in Tables 1, 2, 3, 4, 5, 6 and 7. These tables present the respective summary asset correlations for the BOJ, BOE, and Fed, in all four economic regions. In each table the central banks are listed and the specified asset correlation levels are provided, prior to (pre-ZLB) and during each central bank's ZLB time frame. In the case of the BOJ, there are three ZLB implementations and each is evaluated independently. We define

[7] For example: fiat currency, notes, bonds, *et cetera*.

Table 1 10-year sovereign bond correlations with 10-year sovereign bonds, pre-ZLB and during central bank ZLB implementation

Bank	Bond	Pre-ZLB		During-ZLB	
		Correlation w/ other bonds	Highest correlation with	Correlation w/ other bonds	Highest correlation with
Fed	T-note	HIGH (Pos)	Gilt	HIGH (Pos)	Gilt
BOE	Gilt	HIGH (Pos)	Bund	HIGH (Pos)	T-note
BOJ (1)	JGB	HIGH (Pos)	Bund	LOW (Pos)	Bund
BOJ (2)	JGB	HIGH (Pos)	Bund	LOW (Pos)	T-note
BOJ (3)	JGB	LOW (Pos)	T-note	HIGH (Pos)	Bund

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

Fed US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan, *T-note* 10-year Treasury Note, *Gilt* 10-year UK bond; *JGB* 10-year Japanese Government Bond

the correlation levels as high-level, mid-level, and low-level and present them accordingly as follows: HIGH (Strong) = 75%-100%; MID (Moderate) = 26%-74%; LOW (Weak) = 0%-25%.

The correlation matrices demonstrate the ZLB implementations to have interesting effects on during-ZLB asset correlations when compared to their pre-ZLB values. Of particular note in these correlation analyses is the peculiar behaviour of all regions' financial assets in relation to BOJ ZLB implementations and in the general behaviour of Japanese assets classes. After the third round of BOJ ZLB implementation, the only highly negative correlated asset with equities is the JGB (Table 2). This suggests

Table 2 10-year sovereign bond correlations with equity indices, pre-ZLB and during central bank ZLB implementation

Bank	Bond	Pre-ZLB		During-ZLB	
		Correlation w/ equity indices	Highest correlation with	Correlation w/ equity indices	Highest correlation with
Fed	T-note	HIGH (Neg)	S&P	LOW (Neg)	S&P
BOE	Gilt	MIX (Both)	S&P	LOW (Neg)	S&P
BOJ (1)	JGB	HIGH (Neg)	FTSE	LOW (Mix)	FTSE
BOJ (2)	JGB	HIGH (Pos)	STOXX	MID (Pos)	Nikkei
BOJ (3)	JGB	LOW (Pos)	Nikkei	HIGH (Neg)	S&P

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

S&P Standard & Poor's 500 Composite Index, *FTSE* London stock exchange, *STOXX* STOXX Europe 600 Index, *Nikkei* Tokyo Nikkei 225 stock index, *Fed* US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan, *T-note* 10-year Treasury Note, *Gilt* 10-year UK bond; *JGB* 10-year Japanese Government Bond

Table 3 Gold's correlations with 10-year sovereign bonds, pre-ZLB and during central bank ZLB implementation

Bank	Pre-ZLB			During-ZLB		
	T-note	Gilt	JGB	T-note	Gilt	JGB
Fed	LOW (Neg)			HIGH (Neg)		
BOE		LOW (Neg)			HIGH (Neg)	
BOJ (1)			MID (Pos)			LOW (Pos)
BOJ (2)			MID (Pos)			MID (Pos)
BOJ (3)			HIGH (Pos)			HIGH (Pos)

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

S&P Standard & Poor's 500 Composite Index, *FTSE* London stock exchange, *STOXX* STOXX Europe 600 Index, *Nikkei* Tokyo Nikkei 225 stock index, *Fed* US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan, *T-note* 10-year Treasury Note, *Gilt* 10-year UK bond; *JGB* 10-year Japanese Government Bond

that portfolio managers could look to the JGB as a new tool in managing the risk of their portfolios.

Gold is commonly seen as a hedge for equities. This would suggest a negative or low positive correlation between gold and the equity indices. As bonds and equities are traditionally negatively correlated, then it follows that gold should have a positive correlation with 10-year sovereign bonds. In Tables 3 and 4, however, prior to BOE and Fed ZLB implementations (i.e., pre-ZLB) the Gilt and T-note demonstrate weak negative correlations with gold, while the FTSE and S&P demonstrate weak positive correlations. While gold is likely to still serve as a hedge against falling equity markets, our results may call into question gold's suitability as a perfect or near-perfect hedge

Table 4 Gold's correlation with the equity indices pre-ZLB and during central bank ZLB implementation

Bank	Pre-ZLB			During-ZLB		
	S&P	FTSE	Nikkei	S&P	FTSE	Nikkei
Fed	LOW (Pos)			HIGH (Pos)		
BOE		LOW (Pos)			MID (Pos)	
BOJ (1)			MID (Pos)			LOW (Pos)
BOJ (2)			MID (Pos)			MID (Pos)
BOJ (3)			HIGH (Neg)			LOW (Neg)

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

S&P Standard & Poor's 500 Composite Index, *FTSE* London stock exchange, *STOXX* STOXX Europe 600 Index, *Nikkei* Tokyo Nikkei 225 stock index, *Fed* US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan

Table 5 Silver's correlations with 10-year sovereign bonds, pre-ZLB and during central bank ZLB implementation

Bank	Pre-ZBP			During ZBP		
	T-note	Gilt	JGB	T-note	Gilt	JGB
Fed	MID (Neg)			MID (Neg)		
BOE		MID (Neg)			MID (Neg)	
BOJ (1)			LOW (Neg)			LOW (Pos)
BOJ (2)			HIGH (Pos)			MID (Pos)
BOJ (3)			MID (Neg)			MID (Neg)

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

S&P Standard & Poor's 500 Composite Index, *FTSE* London stock exchange, *STOXX* STOXX Europe 600 Index, *Nikkei* Tokyo Nikkei 225 stock index, *Fed* US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan, *T-note* 10-year Treasury Note, *Gilt* 10-year UK bond; *JGB* 10-year Japanese Government Bond

against equities, especially during BOE and Fed ZLB implementations. The curious behavior of the Japanese correlations certainly suggests alternative portfolio possibilities as well.

In Table 5 we see that the BOE's and Fed's ZLB implementations seem to have no effect on silver's correlation with either the Gilt or T-note, while silver's correlations with the JGBs over three rounds of ZLB are decidedly mixed. The reasons for this are not clear.

When reviewing gold and silver correlations with sovereign debt and equities, due consideration must be given to a crucial difference between these two metals.

Table 6 Silver's correlation with the equity indices, pre-ZLB and during central bank ZLB implementation

Bank	Pre-ZLB			During-ZLB		
	S&P	FTSE	Nikkei	S&P	FTSE	Nikkei
Fed	HIGH (Neg)			HIGH (Pos)		
BOE		MID (Pos)			MID (Pos)	
BOJ (1)			LOW (Pos)			LOW (Neg)
BOJ (2)			MID (Pos)			HIGH (Pos)
BOJ (3)			HIGH (Neg)			LOW (Neg)

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

S&P Standard & Poor's 500 Composite Index, *FTSE* London stock exchange, *STOXX* STOXX Europe 600 Index, *Nikkei* Tokyo Nikkei 225 stock index, *Fed* US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan

Table 7 Equity indices correlations with equity indices, pre-ZLB and during central bank ZLB implementation

Bank	Equity index	Pre-ZLB		During-ZLB	
		Correlation w/ equity indices	Highest correlation with	Correlation w/ equity indices	Highest correlation with
Fed	S&P	HIGH (Pos)	STOXX	HIGH (Pos)	FTSE
BOE	FTSE	HIGH (Pos)	S&P	HIGH (Pos)	S&P
BOJ (1)	Nikkei	MID (Neg)	FTSE	MID (Pos)	FTSE
BOJ (2)	Nikkei	HIGH (Pos)	S&P	HIGH (Pos)	FTSE
BOJ (3)	Nikkei	HIGH (Pos)	Nikkei	MID (Pos)	STOXX

The correlations levels are defined as follows: HIGH (Strong) = 75 %–100 %; MID (Moderate) = 26 %–74 %; LOW (Weak) = 0 %–25 %

S&P Standard & Poor's 500 Composite Index, *FTSE* London stock exchange, *STOXX* STOXX Europe 600 Index, *Nikkei* Tokyo Nikkei 225 stock index, *Fed* US Federal Reserve Bank, *BOE* Bank of England, *BOJ* Bank of Japan

As previously discussed, whereas gold is essentially a precious metal and is often used as a hedge and store of value, silver also possesses these same qualities while possessing many important industrial uses as well. This suggests stronger positive correlations between silver and equities, and possibly more negative correlations with debt, than gold would have with equities and debt. The results in the preceding tables, however, are rather mixed and do not seem to support this logic. It could be that the differences between gold and silver in industrial use are being disregarded by the markets, and both metals are being bought and sold for different purposes other than hedging.

Time-Series Evaluations

In this section we accomplish time-series evaluations of the data to test the robustness of and shed additional light on the correlation analyses accomplished in the preceding section. To do this we evaluate changes in financial asset volatility associated with ZLB implementations. That is, changes in volatility imply changes in specific market activity, which in itself is suggestive of changes in the relative investor positions in any given market. If market correlations are changing, then market volatility should logically increase as trading activity increases and price discovery processes are again set in motion.

The testable hypotheses for these evaluations are:

H_0: volatility does not change
H_A: volatility does change.

To begin this evaluation process we test the data sets for the presence of a unit root using Augmented Dickey-Fuller tests. As is common for financial-economic data, the tests indicate the presence of a unit root for all data sets. This means that the data sets are unstationary and cannot be used directly in their nominal, raw data form. Hence, for these evaluations we first-difference these data by using the change in daily values, which addresses the unit root problem, thereby rendering the data sets stationary. The change in values is defined as:

$$\Delta y_{i,t} = \ln\left(\frac{y_{i,t}}{y_{i,t-1}}\right) \tag{1}$$

where $y_{i,t}$ is the respective equity index value or 10-year bond yield at time t, $y_{i,t-1}$ is the index value or bond yield from the previous daily observation, and $\Delta y_{\mathrm{i,t}}$ is the daily change of the respective equity index or 10-year sovereign bond yield, defined as follows:

$\Delta Nikkei_t$ = Daily change in the Nikkei Index
ΔSP_t = Daily change in the S&P 500 Composite Index
$\Delta FTSE_t$ = Daily change in the London Stock Exchange Index
ΔJGB_t = Daily change in the Japanese Government Bond yield
$\Delta Tnote_t$ = Daily change in the Treasury-note yield
$\Delta Gilt_t$ = Daily change in the Gilt bond yield.

All data sets used in the these evaluations are change-in-daily-value values as described above, with the exception of central bank policy rates, which are used in their nominal, raw form. Since monetary policy rates do not change frequently, if change-of-daily-value values were used for these policy rates, most of the values would be zero. Using a series of zeroes for policy rates leads to less-than-optimal analytical results.

We evaluate the data sets for heteroskedasticity using a White Test. Our null hypothesis is data homoskedasticity. The results from the White Test render F-test p-values much below the 5-percent level, indicating that the data are highly heteroskedastistic. This is typical for financial-economic data. To control for these data characteristics we employ GARCH-type models.

All data sets cover the time period from January 5, 1989 to May 7, 2013, with the exception of the BOJ ZLB implementations. For the BOJ implementations we start with the period for the first ZLB, then the second, and finally the third. The previous implementations are included in the second and third round implementations because their effects are relevant to each of the follow-on implementations. This is on the order of a boxer trying to knock his opponent out during a boxing match. It may take several punches to get that opponent to go down. The effects of prior punches do not necessarily go away, although at the time they may appear to be ineffective. It is often the cumulative effect of a series of punches that eventually leads to the opponent going down. This seems to be the case with the BOJ ZLB implementations as evidenced in the TGARCH results presented later in this section.

As previously noted, there are three BOJ ZLB implementations. For these evaluations we evaluate the impact of ZLB in the following manner:

1. BOJ: First round, before-ZLB: January 5, 1989 to March 2, 1999
2. First round, during-ZLB: March 3, 1999 to Aug 14, 2000

3. Second round, before-ZLB: January 5, 1989 to March 20, 2001
4. Second round, during-ZLB: March 21, 2001 to Jul 17, 2006
5. Third round, before-ZLB: January 5, 1989 to December 19, 2008
6. Third round, during-ZLB: December 22, 2008 to May 7, 2013
7. BOE: Before-ZLB: January 5, 1989 to March 4, 2009
8. During-ZLB: March 5, 2009 to May 7, 2013
9. Fed: Before-ZLB: January 5, 1989 to December 15, 2008
10. During-ZLB: December 16, 2008 to May 7, 2013.

In each GARCH model we employ both intercept and slope dummy variables that represent the pre-ZLB and during-ZLB time frames. This is set to 0 for pre-ZLB and 1 for during-ZLB.

We are interested in not only the significance of any change in the volatility intercept, but also we want to know of the significance of any change in the slope in the relationship (the sensitivity of the relationship) between the policy rates and the financial asset being evaluated. Also included in the models are control variables representing the market (S&P 500 Composite Index or FTSE index) and gold. The S&P index is used for all models as the market control variable except for the model with the S&P as the dependent variable. For the S&P model we use the FTSE index as the market control variable. The S&P Index or the FTSE, as appropriate, is used as a proxy for positive market news. Because the US has the world's largest economy and the S&P 500 is the most liquid and largest equity index in the US, the S&P 500 Composite Index is a good representative for positive market news. This is consistent with common usage of the S&P 500 Composite Index as a proxy for the equity market in such models as the capital asset pricing model (CAPM). In the case of the model with the S&P as the dependent variable, the FTSE is used as the proxy for good news. The gold variable serves as a proxy for negative market news. Negative equity market news often leads to a flight to quality bonds and, if bad enough, to precious commodities such as gold. Only gold is used here since silver, as previously discussed, is a dual-property metal in that it is both a precious metal and an industrial metal; hence, can simultaneously reflect both good and bad news.

An immediate problem arises in modelling these relationships in that all the variables used are endogenous to the system of equations used in determining their values. That is, these variables are all jointly determined. Hence, we have an inherent simultaneity problem. We address this problem by using lagged explanatory variables as instrument variables in the models. We believe that these lagged instrument variables are sufficiently exogenous to proxy for the problematic endogenous variable relationships. Although this lagged explanatory variable approach of addressing simultaneity bias likely introduces problems of its own, we nonetheless believe that this approach renders explanatory variables that are sufficiently exogenous to the system of equations to serve our intended purpose. That is, we do not seek to make any statement regarding causality; rather, only to demonstrate the significance of the volatility relationships between the dependent variable and the explanatory variables.

We employ a TGARCH (1,1) specification for our GARCH analyses (Glosten et al. 1993). We tested various GARCH, TGARCH, EGARCH, and Component GARCH models and our results show strong data asymmetry, which is typical for financial-economic data. From this we elect to use an asymmetric TGARCH model. Further, we evaluated higher order GARCH (*p,q*) specifications up to TGARCH (4,4) and while individual models demonstrate some improvement, the improvement is marginal at best. Hence, in the interest of parsimony and to be consistent with most financial-economic research, we specify the TGARCH models using the (1,1) specification (Nelson 1991). We also use an $AR(1)$ specification for the mean equation. We tested higher-order ARMA specifications and did not find that these higher orders improved the models appreciably; hence, again in the interest of parsimony and to be consistent with most financial-economic research, we use the $AR(1)$ specification (Bollerslev 1986).

The TGARCH (1,1) mean equations for the weekly change in equity index values and 10-year bond yields are as follows:

$$\Delta Nikkei_t = c_0 JPR_{t-1} + D_{Ji,t} + D_{Ji,t} JPR_{t-1} + SP_{t-1} + G_{t-1} + AR(1) + \varepsilon_{i,t} \quad (2)$$

$$\Delta SP_t = c_0 + USPR_{t-1} + D_{US,t} + D_{US,t} USPR_{t-1} + FTSE_{t-1} + G_{t-1} + AR(1) + \varepsilon_{i,t} \quad (3)$$

$$\Delta FTSE_t = c_o + UKPR_{t-1} + D_{UKi,t} + D_{UKI,t} UKPR_{t-1} + SP_{t-1} + G_{t-1} + AR(1) + \varepsilon_{i,t} \quad (4)$$

$$\Delta JGB_t = c_0 + JPR_{t-1} + D_{Ji,t} + D_{Ji,t} JPR_{t-1} + SP_{t-1} + G_{t-1} + AR(1) + \varepsilon_{i,t} \quad (5)$$

$$\Delta Tnote_t = c_0 + USPR_{t-1} + D_{USi,t} + D_{USi,t} USPR_{t-1} + SP_{t-1} + G_{t-1} + AR(1) + \varepsilon_{i,t} \quad (6)$$

$$\Delta Gilt_t = c_0 + UKPR_{t-1} + D_{UKi,t} + D_{UKi,t} UKPR_{t-1} + SP_{t-1} + G_{t-1} + AR(1) + \varepsilon_{i,t} \quad (7)$$

where:

SP_{t-1} = Lagged daily change in value of the S&P 500 Composite Index
$FTSE_{t-1}$ = Lagged daily change variable of the FSTE Index
G_{t-1} = Lagged daily change in value of gold
JPR_{t-1} = Lagged daily Bank of Japan monetary policy rate
$USPR_{t-1}$ = Lagged daily Federal Reserve monetary policy rate
$UKPR_{t-1}$ = Lagged daily Bank of England monetary policy rate
$D_{i,t}$ = Dummy variable indicating pre- and during-ZLB implementation.

The conditional variance equation, $E(\varepsilon_{i,t}^2|\Omega_{t-1})$ with a given information set (Ω_{t-1}) at time period *t*-1 for each mean equation, respectively, is:

$$h_{Nikkei,t} = \omega + \alpha\varepsilon^2_{i,t-1} + \gamma\varepsilon^2_{i,t-1}d_{i,t-1} + \beta h_{i,t-1} + JPR_{t-1} + D_{Ji,t} + D_{Ji,t}JPR_{t-1} + SP_{t-1} + G_{t-1} \quad (8)$$

$$h_{SP,t} = \omega + \alpha\varepsilon^2_{i,t-1} + \gamma\varepsilon^2_{i,t-1}d_{i,t-1} + \beta h_{i,t-1} + USPR_{t-1} + D_{USi,t} + D_{US,t}USPR_{T-1} + FTSE_{t-1}G_{t-1} \quad (9)$$

$$h_{FTSE,t} = \omega + \alpha\varepsilon^2_{i,t-1} + \gamma\varepsilon^2_{i,t-1}d_{i,t-1} + \beta h_{i,t-1} + UKPR_{t-1} + D_{UKi,t} + D_{UKi,t}UKPR_{t-1} + SP_{t-1} + G_{t-1} \quad (10)$$

$$h_{JGB,t} = \omega + \alpha\varepsilon^2_{i,t-1} + \gamma\varepsilon^2_{i,t-1}d_{i,t-1} + \beta h_{i,t-1} + JPR_{t-1} + D_{Ji,t} + D_{Ji.t}JPR_{t-1} + SP_{t-1} + G_{t-1} \quad (11)$$

$$h_{Tnote,t} = \omega + \alpha\varepsilon^2_{i,t-1} + \gamma\varepsilon^2_{i,t-1}d_{i,t-1} + \beta h_{i,t-1} + USPR_{t-1} + D_{USi,t} + D_{USi,t}USPR_{t-1} + SP_{t-1} + G_{t-1} \quad (12)$$

$$h_{Gilt,t} = \omega + \alpha\varepsilon^2_{i,t-1} + \gamma\varepsilon^2_{i,t-1}d_{i,t-1} + \beta h_{i,t-1} + UKPR_{t-1} + D_{UKi,t} + D_{UKi,t}UKPR_{t-1} + SP_{t-1} + G_{t-1} \quad (13)$$

where:

$h_{i,t}$ = conditional variance of $\varepsilon_{i,t}$
ω = variance equation intercept
$\alpha\varepsilon^2_{i,t-1}$ = ARCH parameter term
$\gamma\varepsilon^2_{i,t-1}d_{i,t-1}$= asymmetric leverage term, where $d_{i,t\text{-}1}=1$ if $\varepsilon_{i,t}<0$ and $d_{i,t\text{-}1}=0$ otherwise[8]
$\beta h_{i,t-1}$= GARCH parameter term
All other variables as previously defined

$D_{i,t}$ is a binary dummy variable that equals zero in the pre-ZLB time frame, which is measured from the start of any given data set to the ZLB implementation, in each respective monetary policy region, and one during the during-ZLB implementation. We set $D_{i,t}$ to one for policy changes greater than 25 basis points. Policy changes of less than 25 basis points are not reflected in this analysis. $JPR_{t\text{-}1}$, $UKPR_{t\text{-}1}$, and $USPR_{t\text{-}1}$, are the lagged temporal regional policy rates for the BOJ, BOE, and the Fed, respectively. $SP_{t\text{-}1}$, $FTSE_{t\text{-}1}$, and $G_{t\text{-}1}$ represent the lagged daily changes in the S&P 500 Composite and FTSE Index values, and gold prices. Tables 8, 9, 10 and 11 provide the results of the TGARCH analyses.

In Table 8 the volatility relationships between ZLB implementation and the JGB during the first two BOJ ZLB implementations are insignificant. For the third round of ZLB implementation this volatility relationship suddenly becomes highly significant. This is consistent with us having to set our ZLB range for Japan lower (0.00–0.15 % as opposed to 0.00–0.50 % for the other economic regions) due to Japan having dropped their rates to much lower

[8] If ε_t <0 is considered good news, then ε_t >0 is bad news. Good news impacts $\alpha+\gamma$, whereas bad news affects α only. The resulting differential effect is how asymmetry in volatility is controlled for. If γ does not equal zero the news impact is asymmetric.

Table 8 Japanese 10-year sovereign bond TGARCH evaluation results

Variables	JGB Parameter	1st Round p-value	JGB Parameter	2nd Round p-value	JGB Parameter	3rd Round p-value
Mean equation						
Intercept	−0.000710	0.0604	−0.000776	0.0282	−0.000737	0.0114
$JPR_{t\text{-}1}$	2.71E-06	0.9767	6.92E-05	0.4663	−2.10E-05	0.8470
$D_{Ji,t}$	0.013025	0.0885	0.000847	0.2126	0.004709	0.7719
$D_{Ji,t}JPR_{t\text{-}1}$	−0.460171	0.0671	−0.266158	0.4549	−0.012891	0.9200
$SP_{t\text{-}1}$	0.041913	0.0417	0.015689	0.0022	0.088172	0.0000
$G_{t\text{-}1}$	0.070954	0.0002	0.016697	0.3545	−0.045023	0.0160
Conditional variance equation						
ω	2.61E-05	0.0000	6.31E-06	0.0000	2.09E-05	0.0000
α	0.229024	0.0000	0.132889	0.0000	0.173816	0.0000
γ	0.140554	0.0000	-0.005027	0.6212	0.019532	0.1844
β	0.653958	0.0000	0.859375	0.0000	0.788658	0.0000
$JPR_{t\text{-}1}$	-3.28E-06	0.0000	-8.05E-07	0.0000	-1.55E-06	0.0000
$D_{Ji,t}$	-9.00E-06	0.9707	-3.28E-06	0.7751	0.001367	0.0000
$D_{Ji,t}JPR_{t\text{-}1}$	0.001080	0.8946	0.007755	0.4967	-0.003382	0.0000
$SP_{t\text{-}1}$	-0.000259	0.0594	-0.000190	0.0000	0.000581	0.0000
$G_{t\text{-}1}$	-0.000259	0.0961	-1.80E-05	0.8182	-0.001450	0.0000

This table presents TGARCH results for three Bank of Japan ZLB implementations on the 10-year Japan Government Bond (JGB). The coefficients and p-values for each ZLB implementation are presented, for both the mean and variance equations; $SP_{t\text{-}1}$ Lagged daily change in value of the S&P 500 Composite Index; $FTSE_{t\text{-}1}$ Lagged daily change variable of the FSTE Index; $G_{t\text{-}1}$ Lagged daily change in value of gold; $JPR_{t\text{-}1}$ Lagged daily Bank of Japan monetary policy rate; $USPR_{t\text{-}1}$ Lagged daily Federal Reserve monetary policy rate; $UKPR_{t\text{-}1}$ Lagged daily Bank of England monetary policy rate; $D_{i,t}$ Dummy variable indicating pre- and during-ZLB implementation; ω variance equation intercept; $\alpha = \alpha\varepsilon^2_{i,t-1}$ = ARCH parameter term; $\gamma = \gamma\varepsilon^2_{i,t-1}d_{i,t-1}$= asymmetric leverage term, where $d_{i,t\text{-}1} = 1$ if $\varepsilon_{i,t} < 0$ and $d_{i,t\text{-}1} = 0$ otherwise; $\beta = \beta h_{i,t-1}$= GARCH parameter term

levels than the other regions and doing so more frequently. Further, these results may provide some rationale for the second and third round of ZLB implementation in that the first round did not seem to get the desired response in the financial markets, which brought about the second round, which also apparently did not get the desired results, which in turn brought about the third round, which seems to have finally achieved the desired intent of the BOJ. This appears to be the product of cumulative effects, which is supported by the high volatility persistence indicated in these TGARCH models. Verifying that is outside the scope of this paper.

In Table 9, as with the relationship between the BOJ and the JGB during-ZLB implementation, both the volatility relationships between BOE and Fed ZLB implementations and the Gilt and T-note, respectively, are statistically insignificant. This suggests that sovereign bond trading in both the UK and US are not affected by their respective central bank ZLB implementations. This may be the result of investors' flight to quality during times of economic uncertainty and the

Table 9 UK and US 10-year Sovereign Bond TGARCH Evaluation Results

	Gilt		T-note	
Variables	Parameter	*p*-value	Parameter	*p*-value
Mean equation				
Intercept	0.000679	0.0184	0.000215	0.5422
$UKPR_{t-1}/USPR_{t-1}$	−0.000103	0.0038	−0.000124	0.0709
$D_{UK,t}/D_{US,t}$	0.016690	0.6686	0.010025	0.0100
$D_{UK,t}UKPR_{t-1}/D_{US,t}USPR_{t-1}$	−0.036226	0.6421	−0.081394	0.0055
SP_{t-1}	0.193503	0.0000	−0.041094	0.0021
G_{t-1}	−0.014744	0.1355	0.025332	0.0710
Conditional variance equation				
ω	4.49E-05	0.0000	3.31E-06	0.0000
α	0.492170	0.0000	0.080524	0.0000
γ	−0.134293	0.0000	0.007083	0.4291
β	0.326180	0.0000	0.893631	0.0000
$UKPR_{t-1}/USPR_{t-1}$	−1.20E-06	0.0000	4.25E-08	0.5980
$D_{UK,t}/D_{US,t}$	−0.001779	0.7008	-3.65E-05	0.5901
$D_{UK,t}UKPR_{t-1}/D_{US,t}USPR_{t-1}$	0.003792	0.6823	0.000365	0.4841
SP_{t-1}	−7.66E-05	0.0000	-8.43E-05	0.2936
G_{t-1}	−7.10E-05	0.5060	0.000382	0.0000

This table presents TGARCH results for the Bank of England and the Federal Reserve ZLB implementations on the 10-year UK sovereign bond (Gilt) and 10-year Treasury note (T-note), respectively. The coefficients and *p*-values for each central bank's ZLB implementation are presented, for both the mean and variance equations; *T-note* 10-year Treasury Note, *Gilt* 10-year UK bond; SP_{t-1} Lagged daily change in value of the S&P 500 Composite Index; $FTSE_{t-1}$ Lagged daily change variable of the FSTE Index; G_{t-1} Lagged daily change in value of gold; JPR_{t-1} Lagged daily Bank of Japan monetary policy rate; $USPR_{t-1}$ Lagged daily Federal Reserve monetary policy rate; $UKPR_{t-1}$ Lagged daily Bank of England monetary policy rate;$D_{i,t}$ Dummy variable indicating pre- and during-ZLB implementation; ω variance equation intercept; $\alpha = \alpha\varepsilon^2_{i,t-1}$ = ARCH parameter term; $\gamma = \gamma\varepsilon^2_{i,t-1}d_{i,t-1}$= asymmetric leverage term, where $d_{i,t-1} = 1$ if $\varepsilon_{i,t} < 0$ and $d_{i,t-1} = 0$ otherwise; $\beta = \beta h_{i,t-1}$= GARCH parameter term

central banks' ZLB implementation being accomplished through their large purchases of the respective sovereign debt[9] hence, the central banks satisfying multiple goals simultaneously.[10]

In Table 10 we see essentially the same results for all three rounds of BOJ ZLB implementation effects on the Nikkei as we did for the JGB in Table 8. Hence, the discussion of this table is the same as it is for Table 8, in that apparently it took three rounds of ZLB implementation for the BOJ to achieve their desired intent.

In Table 11 both the intercept and slope volatility variables are insignificant in the BOE ZLB volatility relationship with the FTSE. This is a strange relationship

[9] The monetization of debt.

[10] Three possible central bank goals can be inferred here: first, stimulating the economy through greatly reduced interest rates; second, maintenance of stable sovereign debt markets; and third, providing needed government operating funds.

Table 10 Tokyo Nikkei 225 Stock index TGARCH Evaluation Results

Variables	Nikkei Parameter	1st Round *p*-value	Nikkei Parameter	2nd Round *p*-value	Nikkei Parameter	3rd Round *p*-value
Mean equation						
Intercept	−0.000460	0.1677	−0.000389	0.1126	−0.000114	0.5138
JPR_{t-1}	0.000180	0.1224	0.000158	0.1228	7.25E-05	0.4100
$D_{Ji,t}$	−0.003757	0.7237	0.000431	0.0099	0.000982	0.2410
$D_{Ji,t}JPR_{t-1}$	0.141454	0.6888	0.154558	0.1039	−0.003392	0.6380
SP_{t-1}	0.401449	0.0000	0.436584	0.0000	0.493834	0.0000
G_{t-1}	−0.016705	0.5077	−0.024256	0.7317	−0.005308	0.7007
Conditional variance equation						
ω	1.29E-05	0.0000	1.11E-05	0.0000	1.11E-05	0.0000
α	0.100535	0.0000	0.082819	0.0000	0.082482	0.0000
γ	0.245277	0.0000	0.185045	0.0000	0.168235	0.0000
β	0.734641	0.0000	0.779837	0.0000	0.775848	0.0000
JPR_{t-1}	9.25E-07	0.0436	7.34E-07	0.0363	1.47E-06	0.0000
$D_{Ji,t}$	−6.60E-05	0.6482	−3.22E-06	0.5997	5.19E-05	0.0000
$D_{Ji,t}JPR_{t-1}$	0.002286	0.6350	0.002518	0.6750	−0.000464	0.0000
SP_{t-1}	−0.000743	0.0000	−0.000554	0.0000	−0.000845	0.0000
G_{t-1}	−0.001008	0.0000	−0.000560	0.0000	−0.000396	0.0004

This table presents TGARCH results for three Bank of Japan ZLB implementations on the Nikkei stock index. The coefficients and *p*-values for each ZLB implementation are presented, for both the mean and variance equations; SP_{t-1} Lagged daily change in value of the S&P 500 Composite Index; $FTSE_{t-1}$ Lagged daily change variable of the FSTE Index; G_{t-1} Lagged daily change in value of gold; JPR_{t-1} Lagged daily Bank of Japan monetary policy rate; $USPR_{t-1}$ Lagged daily Federal Reserve monetary policy rate; $UKPR_{t-1}$ Lagged daily Bank of England monetary policy rate; $D_{i,t}$ Dummy variable indicating pre- and during-ZLB implementation; ω variance equation intercept; $\alpha = \alpha\varepsilon^2_{i,t-1}$ = ARCH parameter term; $\gamma = \gamma\varepsilon^2_{i,t-1}d_{i,t-1}$= asymmetric leverage term, where $d_{i,t-1} = 1$ if $\varepsilon_{i,t} < 0$ and $d_{i,t-1} = 0$ otherwise; $\beta = \beta h_{i,t-1}$= GARCH parameter term

implying the UK equity market is not markedly affected by changes in BOE's ZLB implementation. Both the intercept and slope volatility variables are strongly significant in the Fed ZLB and S&P volatility relationship. This result supports observations of pronounced US equity market reactions to Fed policy announcements, particularly with regards to the changes in interest rates, but curiously we do not see the same effects in the UK.

In all cases of the TGARCH analyses above, the sums of the ARCH and GARCH terms (i.e., $\alpha + \beta$) in the variance equations approach one. This suggests that the central banks' ZLB implementations' effects on market volatility are highly persistent.

The results of the TGARCH analyses indicate that with the exception of the third round of BOJ implementation that the ZLB volatility relationships with the respective sovereign bonds are insignificant and that, with the exception of the BOE ZBL implementation, the ZLB volatility relationships with the respective equity indices are significant. In short, this implies that equity markets are affected more by ZLB implementation than are the sovereign bond markets. But as

Table 11 GARCH FTSE and S&P evaluation results

	FTSE		S&P	
Variables	Parameter	*p*-value	Parameter	*p*-value
Mean equation				
Intercept	0.000994	0.0014	−0.000286	0.1996
$UKPR_{t-1}/USPR_{t-1}$	−0.000182	0.0008	0.000112	0.0153
$D_{UK,t}/D_{US,t}$	0.012184	0.5541	−0.000225	0.9191
$D_{UK,t}UKPR_{t-1}/D_{US,t}USPR_{t-1}$	−0.025712	0.5324	0.007767	0.6448
$SP_{t-1}/FTSE_{t-1}$	0.281816	0.0000	−0.005448	0.6543
G_{t-1}	−0.011378	0.3409	−0.005758	0.6262
Conditional variance equation				
ω	−4.74E-06	0.0000	6.45E-08	0.7214
α	0.028181	0.0002	−0.002913	0.0000
γ	0.069749	0.0000	0.158146	0.0000
β	0.910428	0.0000	0.904320	0.0000
UKPRt-1/*USPRt*-1	1.41E-06	0.0000	7.76E-07	0.0000
DUK,t/DUS,t	−0.000118	0.4540	5.88E-05	0.0055
DUK,tUKPRt-1/*DUS,tUSPRt*-1	0.000250	0.4296	−0.000437	0.0073
SPt-1/*FTSEt*-1	−0.000362	0.0000	0.000193	0.0000
Gt-1	0.000113	0.0123	−0.000207	0.0000

This table presents TGARCH results for the Bank of England and the Federal Reserve ZLB implementations on the FTSE and S&P 500 indices, respectively. The coefficients and *p*-values for each central bank's ZLB implementation are presented, for both the mean and variance equations; *S&P* Standard & Poor's 500 Composite Index, *FTSE* London stock exchange; SP_{t-1} Lagged daily change in value of the S&P 500 Composite Index; $FTSE_{t-1}$ Lagged daily change variable of the FSTE Index; G_{t-1} Lagged daily change in value of gold; JPR_{t-1} Lagged daily Bank of Japan monetary policy rate; $USPR_{t-1}$ Lagged daily Federal Reserve monetary policy rate; $UKPR_{t-1}$ Lagged daily Bank of England monetary policy rate; $D_{i,t}$ Dummy variable indicating pre- and during-ZLB implementation; ω variance equation intercept; $\alpha = \alpha\varepsilon^2_{i,t-1}$ = ARCH parameter term; $\gamma = \gamma\varepsilon^2_{i,t-1}d_{i,t-1}$ = asymmetric leverage term, where $d_{i,t-1} = 1$ if $\varepsilon_{i,t} < 0$ and $d_{i,t-1} = 0$ otherwise; $\beta = \beta h_{i,t-1}$ = GARCH parameter term

previously noted, the lack of a significant volatility relationship between ZLB and the sovereign bonds may, at least partly, be due to central banks implementing ZLB by purchasing large amounts of those sovereign bonds.

Conclusion

As discussed earlier, the genesis of this paper comes from a verbal conversation with an investment portfolio manager at a major hedge fund who stated, "One more pragmatic thought might be to study the impact of zero-rate monetary policy on financial asset correlations; that's an issue that keeps portfolio managers up at night." These portfolio managers must simultaneously meet both their specified risk maximums, as stated in their Investment Policy Statements (IPS), and specified rate-of-return targets. Failing to meet these targets does not bode well for the portfolio or its manager; hence, it is imperative that these portfolio managers understand the correlations between different financial asset classes, along with any changes in them in an effort to meet their risk and return objectives.

Our analytical results presented in this paper indicate that the central bank ZLB implementations, in the four regions studied, have in many cases significantly altered the historical financial asset correlations and not necessarily in ways that were predicted. Further, our results indicate that a central bank ZLB implementation in one region affects the asset correlations in other regions, demonstrating that the effects of these ZLB implementations are truly global. For example, prior to central bank ZLB implementations, portfolio managers often held the 10-year sovereign bonds of their respective regions as a means of reducing overall portfolio risk by offsetting equity risk. Since central banks have adopted the heavy use of ZLB-monetary policy after the financial crisis of 2008, the effective use of these bonds for this purpose is rather less certain with one notable exception. Based on our analyses it would seem that the use of Japanese 10-year government bonds for countering equity risk would yield the best results for portfolio managers in all regions and not just Japan. What our results provide a portfolio manager is a means of reassessing portfolio construction in the contemporary financial markets given the changes in financial asset correlations associated with the central bank ZLB implementations. In short, our analytical results present the portfolio managers with new alternatives in constructing optimal portfolios. Further, our analytical results should also be of use to other researchers, investment analysts, traders, fund managers, financial service regulators, and the central banks themselves in monitoring the fragility and stability of the financial system.

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