3. ACTUAL AND EXPECTED INFLATION IN THE U.S.: A TIME-FREQUENCY VIEW

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Abstract

This study examines the correlation between actual and expected inflation in the United States to test whether inflation expectations become self-fulfilling. Wavelet coherence analysis shows that the lead-lag linkage between actual and expected inflation varies according to factors of both frequency and time. The relationship between actual and expected inflation is more robust for frequencies longer than four years than short to medium term ones. We find leading effects of actual inflation on inflation expectations in most periods over medium and low frequencies. However, the structural changes that occurred in 2011 appear to have weakened this effect and no leading role of inflation expectations is found. Therefore, self-fulfilling inflation expectations and the "inflation-expectation" spiral do not appear to pose threats for the U.S. economy.

Keywords: inflation; expectation; self-fulfillment; wavelet analysis; time domain; frequency domain

JEL Classification: C32, E31, D84

Introduction

The estimation of time horizons self-fulfilling inflation expectations and the "inflation-expectation" in the United States (U.S.) using the dynamic nexus between actual and expected inflation remains controversial. Leduc, Sill, and Stark (2007) attribute the high and persistent U.S. inflation rates in the 1970s to a self-fulfilling expectation. If current rates create expectations for future rates, which come to pass simply because of those expectations, the economy may become trapped in an "inflation expectation" spiral, creating challenges for the management of actual and expected inflation. Inflation expectations influence decisions about wages, savings, and investments, thereby transmitting those expectations to the actual economy (Carrasco and Ferreiro, 2013; Hubert and Mirza, 2014). If monetary policy

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reacts to inflation expectations, the effects depend on the direction and strength of causality between actual and expected inflation (Berk, 2002). However, the empirical association between actual and expected inflation is unclear. Both positive and negative relationships have been reported and contradictory results have been documented, depending on the time horizon (Xu *et al.*, 2017a). Policymakers and financial agents pay close attention to inflation expectations. In 2008, surveys of U.S. consumers showed noticeable increases in expected inflation, leading the Federal Reserve Bank (FRB) to respond to concerns about rising inflation and its own credibility (Trehan, 2015). Therefore, an ability to estimate the dynamic correlation between actual and expected inflation can help to anchor inflation expectations and enhance the credibility of central banks (Ball, Mankiw, and Reis, 2005; Reis, 2009).

Although a body of research documents close linkages between actual and expected inflation, there is no consensus on their nature. For example, Mavroeidis, Plagborg-Møller, and Stock (2014) reported that expectations of inflation drive actual inflation in a self-fulfilling spiral whereas Feng and Zhu (2012) found a causal link from actual to expected inflation, and Kim and Lee (2013) suggested the causality is bidirectional. Moreover, the relationship between actual and expected inflation is not constant over time: in certain time frames actual inflation may have either positive or negative effects on expected inflation, whereas at other times expected inflation completely determines current inflation. Therefore, self-fulfilling inflation expectations and "inflation-expectation" spirals appear to occur only in certain time horizons.

This paper is highly intertwined with the existing literature by taking into account the changes in both Time Domain and Frequency Domain with respect to the nexus between actual and expected inflation in the U.S. Su (2010) for instance, has suggested that the relationship between actual and expected inflation rates may change as time goes by. Later, Akoum *et al.,* (2012) asserted that the properties of actual and expected inflation are bound to vary across frequency bands implying that the nexus between two series is likely to be different at distinct time horizons. However, Feng and Zhu (2012) and Rafiq (2014) appealed to methods based on full-sample data such as Granger causality tests and impulse responses to investigate the nexus between actual and expected inflation. These methods suggested a constant relationship between actual and expected inflation and ignore the differences across distinct frequencies. In what is perhaps the latest study of this sort, Xu *et al.,* (2017a) used a Rolling Granger causality test to illustrate the time-variant causal relationship between actual and expected inflation in the U.S. Regrettably, they chose to omit the possible effects of frequency properties and with that reveal a scanty body of research concerning the frequency-related linkage between actual and expected inflation.

Lately, the U.S. economy has experienced many changes and shocks that have induced different monetary policies. The monetary policies implemented around 1980, 2001, and 2008 may have produced changes in actual and expected inflation. Thus, studies of the relationships between actual and expected inflation were likely inaccurate or inconsistent, depending on the sample size and sample selection protocol (Balcilar and Ozdemir, 2013; Balcilar, Ozdemir, and Arslanturk, 2010). Moreover, studies may have reached contradictory conclusions, depending on the time horizon under investigation. The present analysis seeks to uncover the links between actual and expected inflation across both time and frequency. We apply a Wavelet Coherency Analysis based on a continuous wavelet transformation to monthly micro-data on inflation expectations in order to detail the relationship between actual and expected inflation in the U.S. Wavelet Coherency Analysis helps to identify lead-lag links between time series across different horizons, and how these links change over time.

2.Literature Review

A number of studies have reached different conclusions on the relationship between actual and expected inflation. Among those finding inflation expectations to be self-fulfilling, Leduc *et al.*, (2007) showed that prior to 1979, temporary inflationary shocks in the U.S. induced higher inflation expectations and led to prolonged increases in actual inflation. Ueda (2010) investigated the determinants of and influences on inflation expectations in Japan and the U.S., finding that inflation expectations adjusted more quickly than actual inflation to changes in exogenous prices and monetary policy. He concluded that shocks to inflation expectations produced self-fulfilling effects on actual inflation in the U.S. Leduc and Sill (2013) suggested that changes to inflation expectations are a quantitatively important driver of current measures of economic activity and inflation. Taking into account the time-varying relationships between actual and expected inflation, Rafiq (2014) reported that, when inflation expectation is well anchored, shocks to that expectation, particularly in the short term, become increasingly important causes of variation in actual inflation. Koop and Onorante (2012) and Amberger and Fendel (2016) reported that European countries have become more forward-looking in recent years as inflation expectations have played a greater role in determining actual inflation. These results highlight the growing attention to possible self-fulfillment of inflation expectations. Furthermore, given that there is a one-to-one relationship between inflation expectations and growth in the monetary supply, an expected increase in inflation will induce an interest rate increase and sustained rise in inflation (David and Ann, 2014; Păun, Sarlea, and Manta, 2013; MacDonald and Taylor, 1992; Malešević, 2015). Dynamic general equilibrium models also predict that inflation expectations would be self-fulfilling (Girardi, 2014).

Other studies have concluded that actual inflation has significant effects on inflation expectations. The expectations-augmented Phillips Curve predicts that actual and expected inflation would move in a synchronous, one-to-one relationship (Phelps, 1967). Regarding the formation of inflation expectations, Friedman's (1968) adaptive inflation expectation theory asserts that the past trend of actual inflation engenders inflation expectations. Based on the behavior of firms and households, he proposed a completely forward-looking prediction of inflation dynamics as a paradigm for analyzing monetary policy. Following Calvo (1983), the New Keynesian Phillips Curve (NKPC) assumes a stable relationship between the current expectation of future inflation and current actual inflation (Khan and Zhu, 2006), indicating a leading effect of actual inflation on inflation expectation. Despite its success in capturing the dynamics of actual and expected inflation (Gurkaynak and Wright, 2012; Mavroeidis et al., 2014), the NKPC does not reveal all the facts. For example, the model cannot explain the persistence of inflation and the bell-shaped effect of monetary policy on inflation (Rudd and Whelan, 2007). The hybrid NKPC and Sticky Information Phillips Curve (SIPC) were developed to address these shortcomings. The hybrid NKPC combines the backward- and forward-looking pricing behavior of firms and assumes that inflation is determined by past actual inflation and current expectations for future inflation (Gali and Gertler, 1999). Thus, the hybrid NKPC explains the persistence of inflation while preserving the implied leading effect of actual on expected inflation. On the other hand, the SIPC assumes that because of the high cost of collecting and processing information, only a portion of the population updates themselves each period on the current state of the economy and computes optimal prices based on that information (Mankiw and Reis, 2002). Unlike the traditional and hybrid NKPCs, the SIPC posits that current inflation depends on past expectations of the present situation. Empirical evidence supports both the hybrid NKPC and SIPC models (Adam and Padula, 2011; Coibion, 2010; Dupor, Kitamura, and

Tsuruga, 2010; Kiley, 2007; Laforte, 2007), suggesting that both synchronous change and lead-lag relationships may exist between actual and expected inflation.

Furthermore, Chen (2008) demonstrated a significant positive correlation between current actual inflation and expectations for future inflation. Lanne, Luoma, and Luoto (2009) similarly showed that a proportion of households base their expectations on past inflation. The work of Debabrata Patra and Ray (2010) indicated that high and climbing inflation could easily transmit into expectations for continued inflation. Feng and Zhu (2012) documented a causal relationship from actual to expected inflation rather than in the opposite direction. In investigating the formation of inflation expectations, Hubert and Mirza (2014) suggested that lagged inflation constitutes a powerful information source. Analogously, Trehan (2015) stressed that households place a substantial weight on recent inflation data when forming their expectations. Therefore, these studies support the hypothesis that expectations for future inflation are closely related to past actual inflation.

In addition to the unidirectional nexus reported in the above literature, other studies support a bidirectional linkage between actual and expected inflation. Debabrata Patra and Ray (2010) documented bidirectional causality between actual and expected inflation. They argued that persistent inflation pressures would influence inflation expectations, and that sustained expectations for rising inflation might induce actual inflation. In other words, increased inflation may create expectations for higher inflation, which in turn drives up actual inflation. Using impulse responses, Kim and Lee (2013) illustrated that expectation shocks have dynamic effects on actual inflation and that oil and food prices drive inflation expectations. If both inflation and prices rise, the spiral of "inflation-expectation" will occur. On the other hand, some studies challenge the causality between actual and expected inflation. According to Baştürk *et al.,* (2014) there is weak evidence supporting forward-looking inflation, implying that the lead property of actual inflation is not strong enough.

In sum previous research has provided evidence both opposing and supporting a lead-lag relationship between expected and actual inflation or even suggesting bidirectional influences. Nevertheless, these conclusions were drawn from full sample data, which might mask instability across subsamples (Balcilar *et al.*, 2010; Leduc *et al.*, 2007). Structural changes also affect the links between actual and expected inflation. For example, pre-1979 data demonstrated a positive effect of inflation expectations on actual inflation but estimates using post-1979 data did not show a consistent effect. For P.R. China, Su (2010) illustrated robust causality running from actual to expected inflation in various sub-samples, but only prior to 1996. These results suggest that structural changes can twist inflation-expectation spiral. Using the bootstrap Granger full-sample causality test and sub-sample rolling window estimations, Xu *et al.,* (2017a) tested the dynamic causalities between actual and expected inflation in the U.S. Whereas the full-sample results indicated a bidirectional causality, the short-run analysis showed a time-varying causal nexus. Specifically, actual inflation had both positive and negative impacts on expected inflation depending on the sub-period and expectation for inflation exerted only negative effects on actual inflation. Similarly unstable relations between actual and expected inflation were also suggested by Koo, Paya, and Peel (2010) and Cornea, Hommes, and Massaro (2015).

Much of the previous literature disregards possible time influences on the relationship between actual and expected inflation and therefore provide no information on whether the relationship is stable over time. In addition, possible changes over a frequency domain have also been neglected regarding such relationships. There is indeed a research body that analyzes inflation dynamics and other key macroeconomic variables considering the effects of time and frequency. For instance, Kim and In (2005) showed that time-scale

decomposition using wavelet analysis provides a valuable mean of testing the relationship between inflation and stock returns. They reported a positive relationship between stock returns and inflation at short and long scales but negative at intermediate scales. Durai and Bhaduri (2009) revisited the relationship between real stock returns and inflation on the time-frequency decomposition from a wavelet multi-resolution analysis. They suggested that inflation is negatively related to real stock returns in the short and medium scales whereas positive in long term scales. Jiang, Chang, and Li (2015) investigated the dynamic relationship between money growth and inflation in China by applying wavelet analysis. They found that money growth and inflation are positively related in the medium or long term whereas they deviate from such a positive relation in the short term. Wavelet analysis has also been applied to the decomposition of relationships between other economic variables. In particular, Gallegati (2008) used wavelet based correlation to investigate the scaling properties of the lead-lag relationship between stock market returns and economic activity. Soares (2011) explored business cycle synchronization across the EU-15 and the Euro-12 countries using wavelet analysis. Subsequently, Gallegati *et al*., (2011) applied wavelet analysis to the relationship between wage inflation and unemployment. Then, Caraiani (2012) reassessed the relationship between money and output using wavelet power transform and wavelet coherence, documenting a weaker coherence within the Great Moderation and a stronger coherence during the Great Recession. Recently, Xu *et al*., (2017b) extended wavelet analysis into the relationship between social network sentiments and stock returns. The above literature confirms that wavelet analysis is a useful tool to decompose economic variables in a time-frequency framework and test the relationships between different indices at time and frequency domains.

Given that the properties of economic variables vary across frequency bands, or time horizons, the nexus between two series is likely to be different at distinct time horizons (Akoum *et al*., 2012). No research of this nature has been conducted to investigate the connections between actual and expected inflation over time. This paper contributes to the existing literature by examining the linkage between actual and expected inflation in the U.S. from a time and frequency perspective.

3.Methodology

We analyze the nexus between actual and expected inflation using wavelet methodology. Similar to Fourier analysis, wavelets are localized in both time and frequency domains and allow for the analysis of time-frequency dependencies between two time series. Wavelet analysis is however more effective than Fourier analysis for conducting analyses across time, rather than at specific points (Graham, Kiviaho, and Nikkinen, 2012). Wavelet analysis is based on wavelet transformations, which is a process of decomposing and superimposing information. The continuous wavelet transform (CWT) $W_x(\tau, s)$ is obtained by projecting a mother wavelet $\psi(t)$ onto a specified time series $X(T)$. The mother wavelet is as follows:

$$\psi_{\tau,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \quad (1)$$

where: τ denotes the time position and s is the scale parameter, which has an inverse relation to frequency and defines how the wavelet is stretched and dilated. Thus, a lower scale produces a more compressed wavelet that captures higher frequencies of a time series, and vice versa. The CWT is defined as

$$W_x(\tau, s) = \int_{-\infty}^{+\infty} x(t)\psi_{\tau,s}{}^*(t)\, dt \quad (2)$$

where: $\psi_{\tau,s}{}^*(t)$ is the complex conjugate $\psi_{\tau,s}(t)$ of the mother wavelet. Thus, the wavelet

transform decomposes a time series $x(t)$ into a set of base wavelets obtained by translocation and dilation of the mother wavelet $\psi(t)$. The CWT preserves the energy of the examined time series. Following Rua (2012), we adopt the Morlet wavelet:

$$\psi_{\omega_0}(t) = \pi^{-1/4}(e^{i\omega_0 t} - e^{-{\omega_0}^2/2})\, e^{-t^2/2} \tag{3}$$

The parameter ω_0 denotes the number of oscillations within the Gaussian envelope, which is usually set at 6 to guarantee a good balance between time and frequency resolution (Rua, 2012) and thus $e^{-{\omega_0}^2/2}$ can be ignored (Wang, Zhu, and Dou, 2012). In this case, the Morlet wavelet is simplified as follows:

$$\psi(t) = \pi^{-1/4} e^{i\omega_0 t}\, e^{-t^2/2} \tag{4}$$

The wavelet power spectrum captures the relative contribution to the time series variance at each time and each scale:

$${\sigma_x}^2 = \frac{1}{C_\psi}\int_0^{+\infty}\int_{-\infty}^{+\infty} |W_x(\tau,s)|^2 \frac{d\tau ds}{s^2} \tag{5}$$

where: $0 < C_\psi = \int_0^{+\infty} \frac{|\hat{\psi}(\omega)|^2}{\omega} \mathrm{d}\omega < \infty$ and $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(t)$. The cross-wavelet transform of $x(t)$ and $\mathrm{y}(t)$, is defined as $W_{xy}(\tau,s) = W_x(\tau,s){W_y}^*(\tau,s)$ (Hudgins, Friehe, and Mayer, 1993). The cross-wavelet spectrum is correspondingly defined as $\left|W_{x,y}(\tau,s)\right|^2 = |W_x(\tau,s)|^2 \left|{W_y}^*(\tau,s)\right|^2$, implying local covariance between $x(t)$ and $\mathrm{y}(t)$.

The wavelet coherency coefficient measures the local strength of the relationship between two series over time and across frequencies. We adopt the wavelet squared coherency

$$\mathrm{R}^2(\tau,s) = \frac{\left|S(s^{-1}W_{x,y}(\tau,s))\right|^2}{S(s^{-1}|W_x(\tau,s)|^2)S(s^{-1}\left|W_y(\tau,s)\right|^2)}, \text{ where } \mathrm{R}^2(\tau,s) \in [0.1] \tag{6}$$

where: $S(.)$ is the smooth factor normalizing time and scale, and s^{-1} converts to an energy density (see, *e.g.*, Torrence and Webster, 1999). The wavelet coherence can be seen as a localized correlation coefficient in time-frequency space. The closer the value is to 1, the stronger the correlation between $x(t)$ and $\mathrm{y}(t)$, and the opposite is true as the value approaches 0. The significance of such correlation can be tested according to the method proposed by Torrence and Compo (1998).

Following Bloomfield *et al.,* (2004) we estimate the wavelet phase difference between $x(t)$ and $\mathrm{y}(t)$ to measure the lead-lag relationship between actual and expected inflation. The wavelet phase difference is defined as the ratio of the imaginary component of $W_{xy}(\tau,s)$ to the actual component:

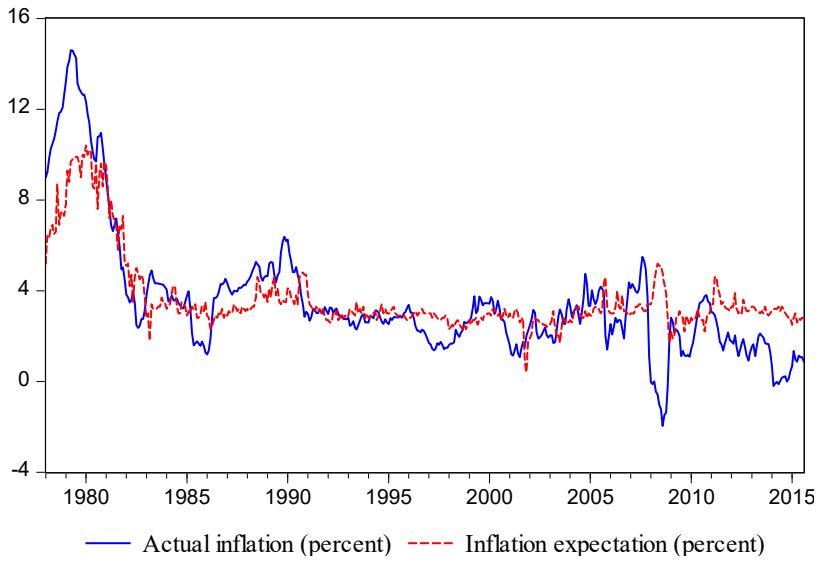
$$\phi(\tau,s) = tan^{-1}\left(\frac{\mathcal{I}\left(W_{xy}(\tau,s)\right)}{\mathcal{R}\left(W_{xy}(\tau,s)\right)}\right), \text{ where } \phi(\tau,s) \in [-\pi,\pi] \tag{7}$$

A 0 phase difference ($\phi(\tau,s) = 0$) means that $x(t)$ and $\mathrm{y}(t)$ are fully synchronized at a specific frequency. The phase difference is graphically represented by an arrow pointing to the right. If $\phi(\tau,s) \in (-\pi/2\,,0)$, $x(t)$ is positively related to and leads $\mathrm{y}(t)$, and the arrow points to Southeast. If $\phi(\tau,s) \in (0,\pi/2)$, then $\mathrm{y}(t)$ leads with the arrow pointing to Northeast. If $\phi(\tau,s) \in [-\pi,-\pi/2)$ or $\phi(\tau,s) \in (\pi/2\,,\pi]$, the two times series are in an antiphase relationship. If $\phi(\tau,s) \in [-\pi,-\pi/2)$, $\mathrm{y}(t)$ is negatively related to and in advance of $x(t)$ and the arrow points to Northwest. If $\phi(\tau,s) \in (\pi/2\,,\pi]$, then $x(t)$ is leading and is negatively related to $\mathrm{y}(t)$ with the arrow pointing to Southwest. A phase difference of π (or $-\pi$) indicates an antiphase correlation and the arrow points to the left. The wavelet phase difference results thereby enable identification of a lead-lag relationship between the two series. If $x(t)$ leads $\mathrm{y}(t)$, then $x(t)$ likely causes $\mathrm{y}(t)$, and vice versa (Grinsted, Moore, and Jevrejeva, 2004; Tiwari, Mutascu, and Andries, 2013).

4.Data

We use monthly data for actual and expected U.S. inflation covering the period January 1978 to August 2015. The Survey of Consumer Attitudes and Behavior, conducted by the University of Michigan Survey Research Center, provides monthly median inflation expectations. Actual inflation corresponds to the growth rate of the Consumer Price Index (CPI) released by the U.S. Bureau of Labor Statistics. Figure 1 shows several important changes in both actual and expected U.S. inflation. First, during 1978-1982, both actual and expected inflation experienced a sharp rise then fall. After several decades of high inflation in the U.S., in 1978-1979 the actual inflation spiked, reaching a crest in April 1979. To ease inflation, the FRB adopted a restrictive monetary policy and raised the federal funds rate to 19% in 1980, inducing a 44-month decline in inflation, from 14.78% to 2.75%. The change in inflation expectations followed a similar trend, with a 10-month lag. The inflation expectation peaked in January 1980 at 10.4%, somewhat lower than the actual inflation rate. The lead-lag relationship during this period was comparatively straightforward. The second significant change occurred during 1983-1991, corresponding to a different policy regime characterized by a dramatic reduction in the volatility of inflation following a deflationary period (Martin and Milas, 2009; Nobay, Paya, and Peel, 2010). During that time, both actual and expected inflation fluctuated modestly. Due to the adjustment of economic policies in the mid-1980s, actual inflation underwent a long-lasting, mild increase over about five years. The trend in expected inflation paralleled that in actual inflation for most of this period, albeit with a consistent delay (Pfajfar and Santoro, 2008).

Figure 1. Actual and Expected U.S. Inflation Rates



In the subsample from 1990 to 1997, actual and expected inflation appeared to be quite stable. The inflation expectation matched actual inflation except during the low inflation of 1996-1997. After 1997, impacted by the Asian financial crisis, actual inflation fluctuated dramatically, and the dislocation was intensified by the 9/11 shock. In 2001, the FRB decreased the interest rate four times during September to December to stimulate economic

growth, boost consumers' confidence and induce higher inflation expectations. The last change appeared around 2007, when the subprime mortgage crisis broke, plunging the nation into financial crisis. During this period, the downturn in the U.S. economy drove down actual inflation to -1.95%, the lowest since 1978. Analogously, inflation expectations declined to a trough in December 2008. Unprecedented easing in monetary policies was implemented to counteract the financial crisis and boost the economy. The quantitative easing (QE) programs in 2008 and 2010 appear to have had the desired effect as actual inflation increased significantly. As a result, during 2006-2011, many sharp ups and downs occurred in actual and expected inflation. However, the leading properties of actual inflation appear to have remained unchanged. Since 2011, when the FRB's target inflation rate dropped to 2.0%, both actual and expected inflation also dropped rapidly. The two QEs in 2012 had little effect in increasing inflation.

Comparing the shocks and trends in actual and expected expectation, it is clear that the two series did not always change in the same direction, and inflation expectations did not show any leading property, as the self-fulfillment theory would predict. Alterations in monetary policy and large economic shocks exerted important effects on actual and expected inflation, making the correlations between them ambiguous. Actual inflation had a leading tendency during the early 1980s and 2006-2011, but the relationship between actual and expected inflation in other periods was not very apparent, suggesting a murky linkage that changed over time.

5.Empirical Results

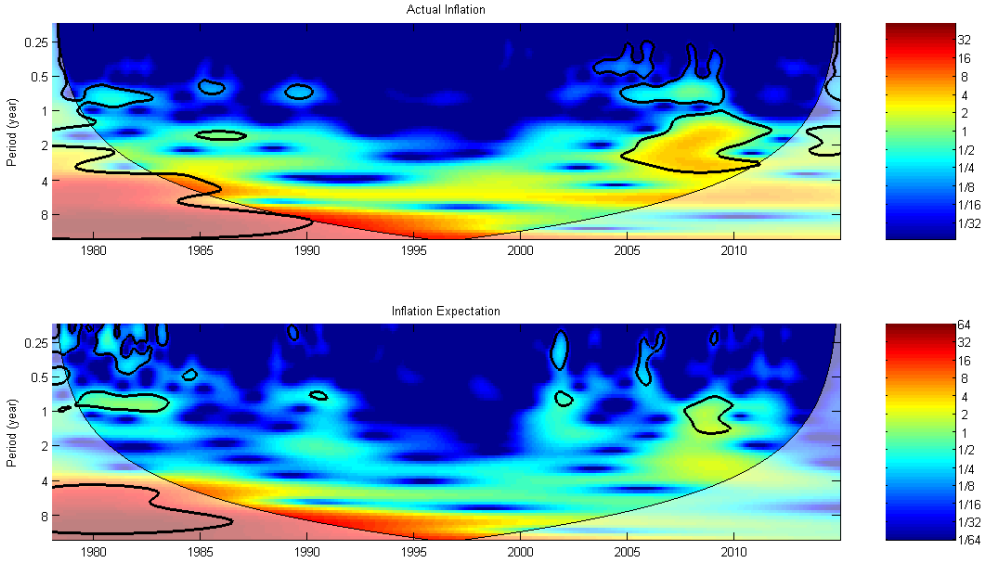
5.1 Morlet Wavelet Power Spectra of Actual and Expected Inflation

Figures 2 present the Morlet wavelet power spectra for actual and expected inflation from 1978 to 2015. Time is represented on the horizontal axis and frequency on the vertical axis. We categorize time periods of less than two years as short-term, those between two and four years as medium-term, and those longer than four years as long-term. The black contour areas represent significance at the 95% confidence interval. The red area denotes a high power value, which drops with movement away from that area. The high power areas represent impulses from events and show that the inflation variable fluctuates severely. The bold, black, upward cone denotes the cone of influence (COI), representing the boundary conditions of the Morlet wavelet transform. In regions outside the COI variables are sensitive to the edge effect and fluctuate accordingly.

Examination of the wavelet power spectra for actual and expected inflation indicates that the spectra are markedly different by time and frequency. When the time frame of the high-frequency region is close to one year, the two variables fluctuate in a relatively different manner. During 1979-1982, which is the period when U.S. monetary policy underwent a structural change, actual inflation fluctuated significantly. Furthermore, the dynamic changes in inflation expectations are more persistent, with observable fluctuations appearing during 1979-1983. Furthermore, inflation expectations show significant changes during the same period at frequencies lower than half a year. Significant fluctuations in actual inflation over a frequency higher than one year are observed during 2003-2009. For the time frame from one to four years, actual and expected inflation show different spectral shapes.

Figure 2

Morlet Wavelet Power Spectrum for Actual and Expected Inflation, 1978–2015



During 2004-2011 - when the real estate market froze, the financial crisis began, and the first two QEs were adopted -severe fluctuations in actual inflation are apparent. However, following economic shocks inflation expectations appear to lag behind actual inflation, with noticeable fluctuations during 2007-2010. This contradicts the theory that inflation expectations influence future actual inflation, casting doubt on the premise that inflation expectations are self-fulfilling. Also noteworthy is that no significant fluctuation in actual or expected inflation is evident at any other frequency or time horizon, particularly at frequencies lower than four years since 1986, reflecting the comparatively stable economic situation. The results indicate that the covariance between actual and expected inflation is associated with both time and frequency horizons, rather than remaining constant or varying only over time.

5.2 Coherence Analysis

The coherence and phrase relationships of actual and expected inflation illustrate covariance and lead-lag linkages between the two indices. Figure 3 shows the Morlet wavelet transform cross-spectra and coherence spectra of actual and expected inflation. The red areas represent high cross-spectral power, indicating that the coherence coefficient between actual and expected inflation is great (close to 1). Blue areas, by contrast, denote small cross-spectral power and a weak coherence coefficient (close to 0), showing that the covariance between actual and expected inflation is weak. Figure 3 identifies both frequency bands (on the vertical axis) and time intervals (on the horizontal axis) where the two indices move together. Moreover, the extent of the correlation between them can be described over time and across frequencies to capture possible changes. The black contour denotes statistical significance at the 95% confidence interval. Analogously, there is a COI in the

cross-spectral power, representing the boundary conditions. The arrows in Figure 3 indicate phase differences between actual and expected inflation.

Figure 3

Morlet Wavelet Transform Cross-Spectra and Coherence Spectra of Actual and Expected Inflation

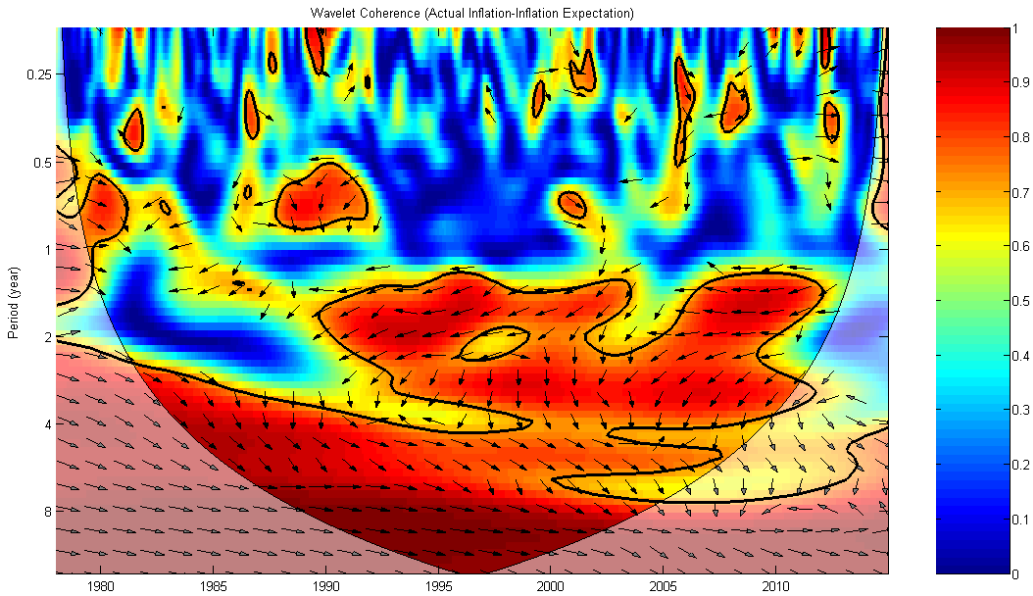


Figure 3 suggests that there were significant short-term links between actual and expected inflation in January 1979-March 1981, June 1987-January 1992, June 1989-June 2003, and March 2004-March 2011. During January 1979-March 1981, the arrows point to Southeast at frequencies lower than one year, meaning that the phase difference between actual and expected inflation is between 0 and $\pi/2$. This result indicates that actual and expected inflation are positively correlated and actual inflation leads inflation expectations. However, the arrows point to Southwest when the linkage is significant over the short term, particularly since 1989 and before June 2003. Therefore, at frequencies around half a year to one year and two years, the phase difference between actual and expected inflation is between $-\pi/2$ and $-\pi$, meaning that actual inflation leads inflation expectation negatively. The negative effect of actual inflation disappears during April 2003-February 2004, and anti-phase movements between them appear during March 2004-March 2011 with arrows pointing to West. Therefore, at a high frequency lasting less than two years, there is a unidirectional leading effect of actual on expected inflation but these effects are different over time. Over the April 1979-July 1980 period in the U.S., actual inflation dropped sharply because of the unprecedentedly high federal funds rate of 19%. Due to the lag behind actual inflation, inflation expectation decreased from September 1979 to May 1982. Affected by a sharp drop in interest rates, actual inflation rose temporarily at the end of 1985, when the economic crisis showed signs of ending. Similar changes in the inflation expectation emerged about one year later, showing that actual inflation had a positive leading effect on inflation expectations. In early 1986, the growth rate in the monetary supply exceeded 13%, resulting

in public concern about inflation. A subsequent rapid increase in actual inflation led to a relatively mild growth in inflation expectations. After 1989, the linkage between actual and expected inflation at high frequencies seems to have become comparatively stable. After high fiscal and foreign trade deficits and severe fluctuations in exchange rates in the 1980s, and economic decline around 1990, the U.S. entered a decade of stable growth. The Clinton administration adopted a contractionary fiscal policy and adaptive monetary policy that produced continuous economic growth from 1991 to 2000, during which time actual inflation and unemployment remained low and stable. Consumers were confident in the government, generating stable inflation expectations. A break appeared around 2003, when the U.S. economy was paralyzed in the aftermath of the 9/11 shock. Under an aggressive government intervention, both actual and expected inflation recovered, particularly inflation expectation maintained a comparatively stable high level during 2002-2005 and the negative correlation between them disappeared during this period in the short-term. As a consequence, except for the effects of the 9/11 shock in 2001, actual inflation exerted stable negative effects on inflation expectations at high frequencies.

The covariance between actual and expected inflation in the medium term is somewhat more persistent than in the short term. As Figure 3 shows, significant correlations appear in 1978-2011, but with quite different phase differences. Specifically, the arrows in 1978-1990 point to Southeast, meaning that phase differences are between 0 and $\pi/2$. Nevertheless, the arrows in 1990-2011 point to Southwest, showing that phase differences are between $-\pi/2$ and $-\pi$. Therefore, correlations over the medium term were positive with a value above 0.8 before 1990, but negative afterwards. The results indicate that the leading effect of actual inflation on inflation expectation encountered a structural change around 1990. Given that medium-term effects translate into lag effects of two to four years, this result suggests that the inflation expectations in 1990 were probably lagged responses to the changes in actual inflation around 1986-1988. The interruption of the correlation coincides with the convening of the first G7 meeting in 1985, when the U.S. dollar plummeted from a 3.5% appreciation to 34% depreciation per year in 1987. The decline in the dollar rippled through to higher import prices, which increased inflation via final consumption and financial costs. The sharp depreciation of the dollar stimulated a remarkable increase in actual inflation and distorted the positive medium-term effect on inflation expectation. During the real estate downturn from January 2004 to February 2011, inflation expectation was relatively stable except in February-November 2008. However, actual inflation fluctuated significantly during this period. Anti-phase movements emerged between actual and expected inflation and actual inflation led.

Over the long-term there is a robust link between actual and expected inflation during 1984-2008. In the frequency of four- to eight-year, a remarkable positive relationship between actual and expected inflation continued for about 25 years, with a correlation coefficient higher than 0.8. Furthermore, the arrows point to Southeast, suggesting that actual inflation led inflation expectation in this period. This finding aligns with the widespread evidence supporting a long-run link between actual and expected inflation (Lanne *et al.*, 2009; Trehan, 2015). During this period, actual inflation preceded inflation expectations, suggesting that unidirectional leading effect of actual inflation remained unchanged as persistent price pressures and pessimism over the economy heightened inflation expectations (Plakandaras *et al.*, 2015). The linkage disappeared in 2011, however, reflecting the more active role of the FRB after 2001 and the structural break in monetary policy around 2000–2002 (Jochmann, 2015; Zhang, Osborn, and Kim, 2008).

Overall, during the past decades, there has been a significant nexus between actual and expected U.S. inflation by time period. Specifically, from 1980 to 1990, actual inflation was positively correlated with inflation expectations, corroborating the findings of Lanne *et al.*, (2009) and Hubert and Mirza (2014). This conclusion is consistent with the findings of Leduc *et al.,* (2007) and Xu *et al.,* (2017a) that expectation shocks exert limited effects on actual inflation in the post-1978 U.S. On the other hand, the leading effect of actual inflation is fairly stable during periods of high and dynamic inflation (*e.g.*, 1980-1990). These results confirm that when inflation fluctuated severely during 1978-1983 and 2004-2011, actual inflation exerted important influences on expectations. Similarly, around the 1987 financial crisis and the 9/11 shock, actual inflation affected inflation expectations at various frequencies. The dynamic changes in actual inflation induced by the financial crisis of 2008 did negatively impact inflation expectations in the short to medium frequencies. This result contradicts that the high opportunity costs of being inattentive when inflation was high and volatile forced Americans to closely follow information about inflation and regularly update their expectations (Pfajfar and Santoro, 2008; Sims, 2003). A plausible explanation may be that agents are confident to believe that the FRB will manage actual inflation. Nevertheless, the correlations during other periods (1990-2011) are related to specific frequencies, contrary to the expectations suggested by mainstream economics. Even so, the results strongly support that actual inflation leads inflation expectations and not the other way around, contradicting the theory that expectations are self-fulfilling. On the other hand, the leading effect of actual inflation on inflation expectation is fairly stable during periods of high and dynamic inflation (e.g., 1980-1990).

Within the frequency domain, both short-term and long-term correlations between actual and expected inflation are evident. In other words, actual inflation exerts both instant and lag effects on inflation expectations. Thus, any analysis of the formation and management of inflation expectations should take into account the lagged effects of inflation. Over frequencies less than one year, the connection between actual and expected inflation is comparatively weak and unstable. However, over lower frequencies, a long-lasting connection between actual and expected inflation is evident. Since 2011, when the FRB's inflation target dropped to 2.0%, however, no significant effects of actual inflation on inflation expectations are shown, indicating that actual inflation is not a leading factor on inflation expectations during this period.

Figure 3 suggests that there were significant short-term links between actual and expected inflation in January 1979-March 1981, June 1987-January 1992, June 1989-June 2003, and March 2004-March 2011. During January 1979-March 1981, the arrows point to Southeast at frequencies lower than one year, meaning that the phase difference between actual and expected inflation is 0 and $\pi/2$. This result indicates that actual and expected inflation are positively correlated and actual inflation leads inflation expectations. However, the arrows point to Southwest when the linkage is significant over the short term, particularly since 1989 and before June 2003. Therefore, at frequencies around half a year to one year and two years, the phase difference between actual and expected inflation is between $-\pi/2$ and $-\pi$, meaning that actual inflation leads inflation expectation negatively. The positive negative effect of actual inflation disappears during April 2003-February 2004, and anti-phase movements between them appear during March 2004-March 2011 with arrows pointing to West. Therefore, in a high frequency lasting less than two years, there is a unidirectional leading role of actual to expected inflation, but the effects are different over time.

5.3 Robustness Analysis

Following Leduc, Sill, and Stark (2007), we estimate the impulse response based on a benchmark VAR with five variables: inflation expectation, actual inflation, a commodity price index in logs, the unemployment rate, and the three-month T-bill rate. The measures of the T-bill, unemployment rate, and commodity price index are annualized. The benchmark VAR is as follows:

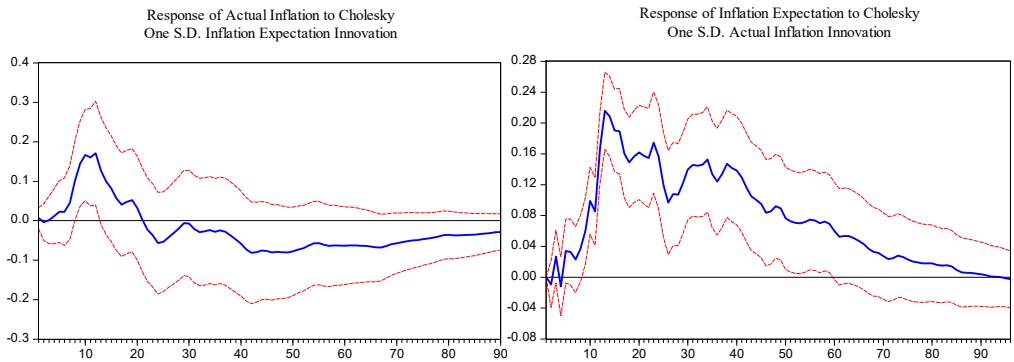
$$Y_t = A(L)Y_{t-1} + \mu_t \tag{8}$$

where: Y_t is a 5×1 vector of data and μ_t is a zero-mean, independent, white noise process with a non-singular covariance matrix. $A(L)$ represents finite-ordered matrix-polynomials in non-negative powers of L, the lag operator. The optimal lag length is determined by the Schwarz criterion (SC). We investigate impulse responses to see if the response of actual inflation to sudden movements in inflation expectation is significant. Figure 4 illustrates the impulse responses, with the first and second columns describing the response of actual and expected inflation, respectively.

Figure 3 shows that the short and long-run correlation between actual and expected inflation is no longer significant after 2011 when the real estate market shows a downturn. Therefore, we test whether the results of impulse response provide similar evidence. These results are presented in Figure 5, with the first and second columns describing the response of actual and expected inflation before and after 2011, respectively.

Figure 4

Impulse Responses of Actual and Expected Inflation



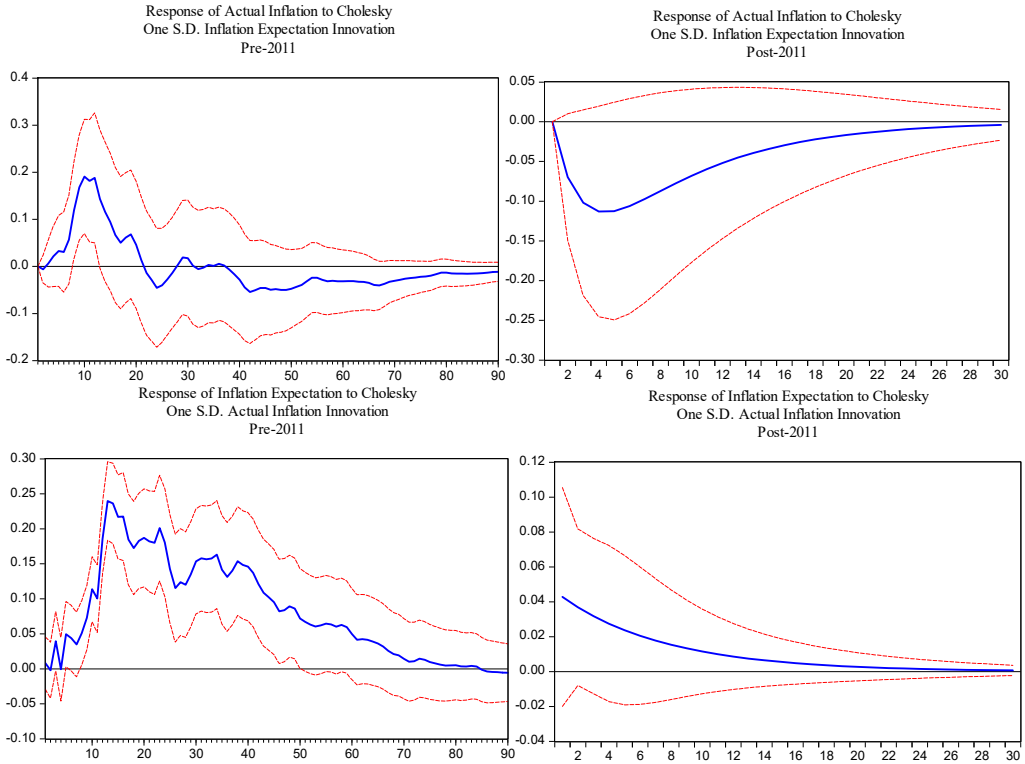
Note: All responses are expressed in percentage terms. The X-axis denotes months. The red lines denote the 90% confidence interval.

Figure 4 shows that a positive, one-time shock to actual inflation leads to a large and persistent increase in inflation expectation. The responses are significantly different from zero for 10 to 60 months after the shock at the 90% confidence level. Inflation expectation rises about 0.21% after one year and then decreases to almost zero after 90 months as a result of a 1% exogenous increase in actual inflation. The impulse responses for inflation expectation are in striking contrast to those of the actual inflation. An unanticipated increase in inflation expectation brings about an initial rise in actual inflation but this increase is quickly reversed and is not significantly different from zero 12 months after the shock. The results of impulse response do suggest that the response of inflation expectation to actual inflation is particularly aggressive. Temporary shocks to inflation expectations do not lead to long-lasting responses in actual inflation. These results are similar to that of Leduc, Sill, and Stark

(2007) in which inflation expectation exerts little effect on actual inflation in the post-1979 era. However, the results of impulse response are based on full-sample data which do not capture the time-variant nexus between actual and expected inflation.

Figure 5

Impulse Responses of Actual and Expected Inflation



Note: All responses are expressed in percentage terms. The pre-2011 period is 1978:01–2011:12 and the post-2011 period is 2012:02–2015:08. The X-axis denotes months. The red lines denote the 90% confidence interval.

As shown in Figure 5, the impulse responses for the post-2011 period are quite different to those of the pre-2011 period. In the pre-2011 sample, the increase in inflation expectation exerts similar effects on actual inflation as in the full-sample period with temporary positive impacts. In the post-2011 period, inflation expectation does not show any effect on actual inflation. Analogously, the impulse responses of inflation expectation to shocks on actual inflation have no significant difference from the full-sample results. In fact, the positive effects of actual inflation on inflation expectation are insignificant in the short and long-run during the post-2011 period. These results are consistent with Figure 3 in which the wavelet coherency coefficients are not significant during 2012-2015 across any frequencies. Therefore, by comparing the results of impulse responses in different periods, we provide evidence for the robustness of Wavelet Coherency Analysis and suggest the time-variant and frequency-related relationship between actual and expected inflation.

6. Discussion and Limitations

The main results from the empirical analysis can be summarized as follows. First, the relationship between actual and expected inflation changes over time and is related to frequency, which differs from those obtained using standard economic tools. On the one hand, past literature either assumed a constant correlation between actual and expected inflation or attributed to a specific structural change. Using U.S. data, Ueda (2010) calculated the correlation between actual inflation and one-year forward inflation expectation. He found that households' inflation expectations led actual inflation for one quarter. Ueda went on to say that impulse responses of inflation expectations and actual inflation to exogenous structural shocks demonstrate that inflation expectations respond more quickly than actual inflation. Meanwhile, actual inflation reacted significantly to an inflation expectations shock in the U.S., consistent with the self-fulfilling property shown by Leduc *et al*., (2007). A fundamental difference between Leduc *et al*., (2007) and Ueda (2010) is that the leading effect of inflation expectation existed in pre-1979 and 1971-2007, respectively. These two papers adopted the same method of impulse response function. However, the results based on post-1979 data in Leduc *et al*., (2007) suggested that inflation expectations exerted no leading effect on actual inflation. Our study consistently notes that the relationship between actual and expected inflation changes over time. We find results similar to Leduc *et al*., (2007) that inflation expectation has no leading effect on actual inflation since 1979, but these two series are still closely related with each other. Studies relying on constant relationships fail to consider possible changes caused by unknown structural changes, e.g., the economic crisis in 1990 (Gan, 1992) and the 2008 financial crisis.

On the other hand, previous studies neglect the effects of frequency in a time-varying relationship between actual and expected inflation. Xu *et al*., (2017a) revisited the causal relationship between actual and expected inflation in the U.S. using rolling window estimations which specified a fixed window size of 60 months. They demonstrated that such linkages are different over a full-sample period and each sub-sample period, thus confirming our results of a time-varying relationship. The full-sample data covered January 1978 to November 2015 and documented a causality from actual to expected inflation. This result is aligned with our findings at low frequencies. As shown in Figure 3, the arrows at frequencies higher than eight years point to Southeast, meaning that actual inflation led inflation expectation in the long-term. Our results are similar to their sub-sample results before 1999. As noted in Xu *et al.,* (2017a), the positive causality from actual to expected inflation disappeared since 1999 (excluding the 2005-2007 period). Figure 3 shows that the leading effect of actual on expected inflation disappeared since 2002 at a frequency of five years which equals the window size used by Xu *et al*., (2017a). However, the results based on post-1999 data are different. Whereas Xu *et al*., (2017a) showed a negative causality from expected to actual inflation during 1999-2011 (excluding 2005), we did not find a significant correlation since 2002.

Second, the wavelet correlation shows a negative relationship in the short-term and medium-term, but a positive relationship in the long-term. The results suggest that an increase in actual inflation may decrease inflation expectation in the short- and medium-term, but increase it in the long-term. At highest frequencies (less than one year), we did not find a significant relationship, particularly since 1992, confirming that there was no co-movement between short-term actual and expected inflation. At frequencies between one to two years, there is a comparatively stable negative leading effect of actual inflation on inflation expectation. The relationships at frequencies between two to four years change in 1990 from

positive to negative. Only at frequencies higher than four years, the relationships between actual and expected inflation remain stable. Studies on anchoring of inflation expectations argued that short-term inflation expectation is not anchored (Autrup and Grothe, 2014; Beechey *et al*., 2011), but long-term inflation expectation is found to be well-anchored (Strohsal and Winkelmann, 2015). Well-anchored inflation expectations should not respond to changes in actual inflation. In contrast, our study suggests that movements of actual inflation led inflation expectation except for frequencies less than one year. In other words, short-term inflation expectation is more likely to be anchored because it was not affected by actual inflation while for medium- and long-term inflation expectations, they were not anchored. This result differs from Strohsal and Winkelmann (2015), in which inflation expectations were shown to be well-anchored for decades. Besides, they documented that long-term inflation expectations are better anchored than short-term inflation expectations. We provide evidence regarding the de-anchoring of inflation expectations at frequencies higher than one year. In fact, our result conform the sticky information theory which suggests that past inflation is the main information source in forming inflation expectations and agents are sluggish in updating information. Carroll (2003) and Mankiw and Reis (2002) found that the average information updating frequency is 11-12 months. Similarly, Khan and Zhu (2006) estimated average durations that range from three quarters to over seven quarters. Consequently, short-term changes in actual inflation exert little effect on inflation expectation because such information has not been absorbed by most economic agents.

Third, actual inflation shows a significant leading effect on inflation expectation rather than the other way around. Inflation expectations have exerted no leading effect on actual inflation, suggesting that inflation is not supposed to drift persistently. This finding contradicts the self-fulfilling property of inflation expectations which indicates higher inflation expectation leads to increasing actual inflation, but supports Trehan (2015), who argued that agents focus on past actual inflation in forming inflation expectations. Thus, one would expect the gradual reduction of slack to be associated with less downward price pressure and concern about excessive inflation induced by inflation expectation. The leading role of actual inflation has been widely supported in the literature. For example, Lanne *et al*., (2009) found that a significant proportion of households base their expectations on past inflation, and the widely adopted hybrid NKPC suggests a positive correlation between current inflation and expected future inflation. Thus, the effect of inflation expectation on actual inflation is limited. A rising exchange rate deserves more attention as a potential factor impacting actual inflation (Fischer, 2015). Our findings sharply contradict those of Nautz and Strohsal (2015), who claimed that inflation expectations were well anchored during 2004-2009 and unanchored after that. In contrast, we argue that actual inflation drove inflation expectations at the medium and low frequencies higher than two years, meaning it was not well anchored until 2011. In contrast, such a relationship is not found since 2011, showing that the actual inflation is not a driver of inflation expectations, at least at high frequencies.

A correlation between actual and expected inflation undoubtedly exists and varies across frequencies and over time, highlighting the importance of assessing the role of actual inflation in altering inflation expectations. Furthermore, the heterogeneity in terms of frequency and time should be considered when modeling the linkage between actual and expected inflation. Long-term inflation expectations in the U.S. appear to have remained generally stable since the late 1990s. The reason for that stability is open to debate, but the robust positive effects of actual inflation on inflation expectations over the long-term suggest that the FRB's actions to maintain inflation at relatively low and stable rates for three decades are an important part of the explanation. Since 2011, ongoing economic slacks are one

reason why actual inflation has remained low (Fischer, 2015). During the 2008 financial crisis the unemployment rate rose to 10%, making a lengthy period of high unemployment inevitable. Although actual inflation decreased, inflation expectations appeared to remain stable. Therefore, actual inflation has had no significant effect on inflation expectations at any frequency since 2011.

The wavelet analysis has been broadly applied in the economic arena. However, this approach has never been adopted to study the relationship between actual and expected inflation. The wavelet analysis reveals some complex patterns of time series and corresponding relationships that cannot be identified by standard economic tools. Particularly, examining whether regions in time frequency space have a consistent phase relationship is suggestive of causality between the time series (Grinsted *et al.,* 2004). We explicitly acknowledge not having tested for causality in a Granger sense. Therefore, future research should attempt to estimate causalities in frequency and time domains to provide more detailed information about the relationship between actual and expected inflation.

7. Conclusion

This article has assessed the correlation between actual and expected inflation in the U.S. through a wavelet analysis that effectively captures features that vary by both frequency and time within a unified framework. A time-frequency view of the relationship between actual and expected inflation over the last 38 years presents variances by both frequency and time. The correlation between actual and expected inflation appears to be more robust at time horizons of four to eight years than at shorter intervals. Moreover, actual inflation shows significant leading properties on expected inflation. We find no one-for-one shift between actual and expected inflation as indicated by the “expectations augmented” Phillips Curve. Moreover, actual inflation lead inflation expectation rather than the other way around. The relationship between actual and expected inflation in the U.S. is unstable over time but fits well with the transitions and structural changes in monetary policies and economic shocks. It is crucial for policymakers to know whether inflation expectations predict future inflation. Our results indicate that this has not been the case since 1978 and therefore the inflation expectation spiral does not pose a threat to the management of inflation.

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