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Relationships between inflation, output growth, and uncertainty in the era of inflation stabilization: a multicountry study

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Abstract
Since the 1990s, central banks in many industrialized and developing countries have adopted similar policy strategies for stabilizing inflation. In this context, it has been argued that during common policy periods, the relationships between inflation, output growth, and their uncertainties are stable and more uniform across countries. We intend to verify this for 19 countries using both linear and non-linear bivariate GARCH-in-mean models. According to our findings, the non-linear regime-dependent model performs better in most of the sampled countries. It has been observed that inflation uncertainty has a significant impact on inflation, particularly in developing countries. Nominal and real uncertainty affect output growth primarily during periods of economic contraction. Although nominal uncertainty inhibits output growth, real uncertainty has mixed effects. In most countries, negative growth shocks result in greater output growth volatility than positive growth shocks. Furthermore, in some countries, output growth significantly increases inflation only in high-inflation regimes.

Keywords Inflation · Output growth · Uncertainty · Threshold model

JEL Classification C32 · C51 · E31 · E32

1 Introduction

Understanding the relationships between inflation, output growth, and their uncertainties is crucial, as the issue has a substantial impact on the economic policies pursued by monetary authorities (Greenspan 2004). However, there is a great deal of complexity associated with how uncertainties (both nominal and real) evolve and how they

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interact with inflation and output growth.[1] According to Friedman's (1977) widely recognized argument, high inflation causes the monetary authority to respond with erratic policy, thereby increasing uncertainty regarding the future rate of inflation. This increase in inflation uncertainty distorts relative prices, impairs the efficient allocation of resources, and consequently retards output growth. Therefore, a reduction in inflation is necessary to reduce its welfare costs. It is this argument that strengthened many countries' decisions to adopt price stability during the 1990s. Over the last two and a half decades, since the 1990s, the monetary authorities of a large number of industrialized and developing countries have adopted inflation targeting (IT) strategies in order to improve economic efficiency. There was also a group of countries that did not target inflation explicitly, but instead adopted alternative policies such as monetary, exchange rate, or multiple targeting frameworks to stabilize prices (Mishkin and Schmidt-Hebbel 2001; Walsh 2009). Despite substantial controversy surrounding the effectiveness of inflation targeting strategies over other policy alternatives, several researchers have noted that both inflation targeting and non-inflation targeting countries have experienced significant reductions in inflation and improved average growth rates during common policy periods. In addition, both inflation-targeting and non-inflation-targeting low-income economies experienced large reductions in the volatility of inflation and output growth (Ball and Sheridan 2004; Dueker and Fischer 2006; Lin and Ye 2007). Since the data generating processes of both the levels and volatilities of inflation and output growth exhibited similar patterns across multiple nations, it is likely that the dynamic interaction between these variables will also display similar patterns across economies (Hartmann and Roestel 2013). In fact, a recent finding by Hartmann and Roestel (2013) supports empirical unanimity in 34 countries regarding the impact of nominal uncertainty on output growth over the period from 1990 to 2010.

The primary objective of this study is to examine whether the causal relationships between inflation, output growth, and their respective uncertainties are stable and uniform for a group of inflation-targeting and non-inflation-targeting countries during inflation-targeting/common-policy periods. To this end, we have incorporated a non-linear dimension into the existing modelling approach. It has been evident that many countries, despite having similar benefits from macroeconomic policies (either inflation-targeted or non-inflation-targeted policies), exhibited significant heterogeneity in terms of average inflation and output growth rates. Even in the countries that implemented inflation targeting policies, there were inflation differences. The variation is primarily attributed to the variations in the frameworks adopted by these nations for addressing inflation, including differences in the target price index, target width, target horizon, accountability for target misses, and overall transparency and accountability of the monetary authority (Mishkin and Schmidt-Hebbel 2001). De Haan (2010) has

[1] Several competing theories have been proposed in the last three decades in order to explain the above linkages. Simultaneously, a substantial amount of empirical research has been carried out to determine the true nature of these relationships [see Fountas et al. (2006), Bredin and Fountas (2009), Bhar and Mallik (2013), and Conrad and Karanasos (2015) for details on the theories and empirical works]. The empirical results, however, are not conclusive; rather, they vary significantly across countries depending on monetary policy regimes and economic development of a country.

observed disparities in inflation across Euro area countries. After a brief period of initial convergence in the 1990s, the Euro area's inflation rates started to diverge in 1999, and ever since then, the annual rates have varied within a 1-percent standard deviation. In the case of output growth, Benalal et al. (2006) noted that since the mid-1990s, GDP growth has differed across the euro area countries. In some countries, growth rates have been consistently higher than the euro area average, whereas in others, they have been lower. All these empirical findings lead us to think that country-specific heterogeneity in terms of average inflation and output growth rates may have a significant impact on inflation-growth-uncertainty relationships. In light of this, our study proposes a non-linear model to examine regime-dependent interactions between inflation, output growth, and their uncertainties. Specifically, we intend to address the following issues. First, do the relationships vary with country-specific levels of inflation and output growth? Second, if the majority of economies' interactions are regime-dependent, is it possible to identify common patterns in the relationships between nations? Third, if it is found that the interactions between a group of countries are stable, can we observe uniformity in the causal relationships? Lastly, we test the spillover effects between nominal and real uncertainty and discuss how these uncertainties are affected by past inflation and output growth shocks.

The GARCH model (Bollerslev 1986) and its multivariate extension, i.e., multivariate GARCH (MGARCH) (Bollerslev 1990) have been widely used in the empirical literature to measure inflation and output growth uncertainties. Following Grier and Perry (2000), several studies have adopted the bivariate GARCH-in-mean (GARCH-M) model to examine the impacts of nominal and real uncertainty on output growth and inflation. The advantage of using the bivariate GARCH-M model over the 'two-step' procedure[2] is that estimates of uncertainties and their associations with economic performance can be assessed together. Although the VAR-GARCH-M model is widely used to generate uncertainty, the estimates are, by construction, invariant to past shocks in inflation and output growth. Grier et al. (2004) and Shields et al. (2005) have proposed an asymmetric GARCH (AGARCH) model in a bivariate framework in which positive and negative shocks have different effects on volatility. Several empirical studies (Grier and Perry 2000; Elder 2004; Grier et al. 2004; Shields et al. 2005; Bredin and Fountas 2005; Bredin and Fountas 2009; Bhar and Mallik 2013) have used the VAR-AGARCH-M framework to examine the various relationships between inflation, output growth, and their uncertainties. However, the empirical evidence is inconsistent and diverse. While reasons for mixed results could partly be attributed to the differences in the sample periods and frequencies of the data sets used, more importantly, it is the methodology or modelling approach applied that would explain the varied findings. Neanidis and Savva (2013) have argued that, when modelling uncertainties and their associations with inflation and growth, it is crucial to account for the regime-switching behaviours of inflation and output growth; failure to do so may lead to erroneous conclusions. In this regard, it is important to mention that the application of a regime-dependent model in a bivariate framework is rare, even

[2] In the 'two-step' procedure (Fountas et al. 2002; Fountas and Karanasos 2007), a bivariate GARCH type model has been employed in the first step to estimate the conditional volatilities of inflation and output growth, and then in the second step, a VAR setup with inflation, growth, and their respective volatilities has been used to examine different possible causal relationships.

for developed economies (Chang and He 2010; Caglayan et al. 2015; Neanidis and Savva 2013; Chowdhury et al. 2018). Chang and He (2010) and Caglayan et al. (2015) have applied a bivariate Markov switching model where the regimes are governed by unobservable state variables. In addition, these two studies have only considered one linkage, namely the impact of inflation uncertainty on output growth in the USA. In contrast, Neanidis and Savva (2013) and Chowdhury et al. (2018) have adopted a threshold bivariate VAR model where the regimes are determined by observed levels of inflation and output growth and then applied this model to examine each of the four impacts of macroeconomic uncertainties on inflation and output growth. Along the same line, we have proposed a self-exciting threshold VAR-asymmetric GARCH-in-mean (henceforth SETVAR-AGARCH-M) to study regime-dependent relationships. Here, the regimes are determined by the levels of inflation and output growth rates. The threshold values are assumed to be known and taken to be the average values of inflation and output growth in a particular country. The use of observed thresholds is all the more important as we intend to investigate how the heterogeneous levels of inflation and output growth prevalent in multiple countries influence the inflation-growth-uncertainty relationships. Unlike Neanidis and Savva (2013), and Chowdhury et al. (2018), our study tests the bidirectional interactions between the levels of inflation and output growth in addition to the 'in-mean' effects. Furthermore, ours is the first attempt to implement a threshold bivariate model in some developed and emerging countries.[3]

Our study reveals that the relationships between inflation, output growth, and uncertainty are regime-dependent in the majority of countries. Furthermore, macroeconomic uncertainties have a more pronounced impact on output growth than on inflation. Both nominal and real uncertainty affect output growth, mainly during economic contractions. We observe an asymmetrical impact of past output growth shocks on its uncertainty. In most countries, negative output growth shocks significantly increase real uncertainty. In addition, the majority of nations exhibit significant (unidirectional or bidirectional) spillover between inflation and output growth uncertainties. The rest of the paper proceeds as follows. Literature reviews are summarized in Sect. 2. Section 3 introduces the models. The results are discussed in Sect. 4, and Sect. 5 concludes the paper.

2 Literature review

There is a vast amount of macroeconomic literature on the interactions between inflation and output growth. The majority of theoretical studies conclude that a rise in inflation either slows or has no effect on output growth. According to Stockman (1981), higher inflation rates can result in lower real balances for acquiring capital stock, which in turn reduces the growth of output. Endogenous growth models provide additional support for inflation's negative impact on economic growth (Gomme

[3] Except Neanidis and Savva (2013), who consider data from G7 countries, other studies mainly focus on the USA.

1993; Jones and Manuelli 1995; Gillman and Kejak 2005). According to these models, higher inflation rates act as a tax on capital, which lowers the rate of return on investment and, ultimately, output growth. Although the mean spillover effect has been the subject of numerous studies, more recent research has focused on the interactions between macroeconomic uncertainty and inflation and output growth. In his Nobel address, Friedman (1977) argued that an increase in inflation may lead to an inconsistent monetary policy response, which can increase uncertainty about future inflation and slow down output growth. In contrast, Dotsey and Sarte (2000), using a cash-in-advance framework, demonstrated that higher inflation uncertainty may also result in higher output growth. This argument is based on the precautionary motive of risk-averse economic agents: more inflation uncertainty increases savings and, consequently, investment and growth. Regarding the influence of inflation uncertainty on inflation, Cukierman and Meltzer (1986) argued that the public is uncertain about the rate of money supply growth and the objective function of policymakers. In this scenario, higher inflation uncertainty could prompt policymakers to adopt an expansionary monetary policy to generate an inflation surprise in an effort to achieve output gains. As opposed to this viewpoint, Holland (1995) argued that central banks, whose primary goal is price stability, would adopt a tighter monetary policy in an environment of increased inflation uncertainty, which would reduce future inflation. There are also differing opinions regarding the effect of output growth uncertainty on output growth. This effect could be negative, neutral, or positive. According to Black (1987), the effect of output growth volatility on output growth is positive. The arguments of Bernanke (1983) and Pindyck (1991) suggest a negative relationship between these two variables. According to their view, entrepreneurs should take into account business fluctuations when estimating investment returns. The higher the output fluctuation, the greater the risk associated with investment projects, which tends to delay or cancel investment projects. In turn, the decline in investment reduces output growth.[4]

Since there were different theories, many empirical studies over the last three decades were conducted to examine the true nature of the relationships. However, empirical results are also inconsistent and diverse.[5] Consequently, all theories have varying degrees of empirical support. In their study, Hartmann and Roestel (2013) indicated that a long period of data is particularly vulnerable to structural instability due to country- and era-specific monetary policy changes. The authors have analyzed a specific period, known as the era of inflation stabilization, for a large group of developed and developing economies. During this period, the central banks of these countries conducted monetary policy in a similar way to target or stabilize inflation. Using a VAR-GARCH-M model, the authors found that both inflation and inflation uncertainty have a significant negative effect on output growth in most countries. Hartmann and Roestel (2013) concluded that the ambiguity of contradictory findings regarding the relationships would be substantially reduced if the analysis was centred on a common policy period for a set of distinct countries. Nonetheless, few other studies have found significant heterogeneity in terms of level-uncertainty relationships between

[4] See, Fountas et al. (2006) and Conrad and Karanasos (2015) for details of the theories.

[5] Fountas et al. (2006), Neanidis and Savva (2013) and Chowdhury et al. (2018) cite a large number of empirical studies that employ linear bivariate models to investigate the relationships.

countries that have even adopted common monetary policies. Using a time-varying GARCH model, Caporale and Kontonikas (2009) noted a considerable degree of heterogeneity among European Monetary Union (EMU) countries in terms of short- and long-term uncertainty, and their interactions with the inflation rate. In a separate study, Fountas et al. (2004) found that inflation uncertainty does not affect output growth uniformly across Eurozone countries. It is true that countries that adopted similar monetary policies experienced low inflation rates and favourable economic growth. However, there is significant heterogeneity in average inflation and output growth rates of these countries. Using linear and regime-dependent models, our study attempts to determine whether the presence of inflation and output growth disparities affects the level-volatility relationships for a group of developed and developing countries during the common policy periods.

Over the last two decades, a growing body of research has tried to establish the usefulness of the state of the economy and its influence on macroeconomic relationships. In fact, empirical studies have demonstrated, utilizing nonlinear threshold models, that the impact of inflation on output growth is asymmetric and depends on the level of inflation [see, among others, Ghosh and Phillips (1998), Khan and Senhadji (2001), Burdekin et al. (2004), and Gillman and Kejak (2005)]. A few recent studies have also investigated the asymmetric effects of macroeconomic uncertainty on output growth and inflation. Using a bivariate Markov regime switching model for the USA, Chang and He (2010) found that inflation uncertainty inhibits output growth significantly in both high- and low-inflation regimes. However, the magnitude of the effect is greater in the high inflation regime than in the low regime. Alternatively, Caglayan et al. (2015) analyzed the same effect for the USA under different output growth regimes. Employing a Markov switching model, they have shown that nominal uncertainty has a more severe effect on output growth in low growth regime. In recessions, the magnitude is found to be greater than in expansions. Chang (2012) examined the relationship between inflation and inflation uncertainty in the USA by incorporating the regime switching behaviour of inflation. The results indicate that regardless of inflation regimes, inflation uncertainty has no significant effect on inflation. Using data from 100 countries, García-Herrero and Vilarrubia (2007) demonstrated that output growth volatility exhibits a ‘Laffer curve’ effect. This indicates that a moderate level of volatility promotes growth while a high level of uncertainty substantially reduces it. Henry and Olekalns (2002) analyzed the impact of expansion and contraction on the interactions between output growth and its uncertainty in the USA. According to their findings, a recession leads to higher output growth uncertainty, which reduces subsequent economic growth. Neanidis and Savva (2013) adopted a bivariate threshold model to examine the joint effects of nominal and real uncertainties on inflation and growth in the G7. Their findings indicate that higher real uncertainty increases output growth primarily in low-growth regimes. In addition, nominal uncertainty increases inflation in the majority of G7 countries, which is consistent with the argument of Cukierman and Meltzer (1986). Using a similar type of bivariate regime switching model for the USA and the UK, Chowdhury et al. (2018) found that inflation uncertainty has a negative impact on output growth during economic downturns. In a similar vein, we have proposed a nonlinear model to examine regime-dependent relationships between inflation, output growth, and uncertainty. It is important to note that all of the above studies, with the exception of Neanidis and Savva (2013), use the regime switching model primarily in the context of the USA. In this study, we examine some developing and a few Eurozone countries in an attempt to identify any common patterns in the nonlinear linkages, thereby extending the empirical literature.

3 Methodology

This section introduces three models of inflation (x_t) and output growth (y_t), namely VAR-GARCH-M, VAR-AGARCH-M, and SETVAR-AGARCH-M. All models adhere to the simultaneous estimation framework, which estimates the conditional means and variances of inflation and output growth simultaneously (Grier and Perry 2000; Grier et al. 2004). The VAR-GARCH-M model is specified by Eqs. (1) and (2), where the first equation describes the conditional means and the second describes the conditional variances of inflation and output growth.

$$Z_t = \mu + \sum_{i=1}^{p} \Psi_i Z_{t-i} + \Gamma\sqrt{h_t} + \varepsilon_t,\ \varepsilon_t|\Omega_{t-1} \sim N(0, H_t) \tag{1}$$

$$H_t = CC' + A\varepsilon_{t-1}\varepsilon_{t-1}{}' A' + BH_{t-1}B' \tag{2}$$

where $Z_t = \begin{bmatrix} x_t \\ y_t \end{bmatrix}$, $\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}$, $\Psi_i = \begin{bmatrix} \psi_{i,11} & \psi_{i,12} \\ \psi_{i,21} & \psi_{i,22} \end{bmatrix}$, p is the optimal lag order, $H_t = \begin{bmatrix} h_{x,t} & h_{xy,t} \\ h_{yx,t} & h_{y,t} \end{bmatrix}$, $\Gamma = \begin{bmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{bmatrix}$, $\sqrt{h_t} = \begin{bmatrix} \sqrt{h_{x,t}} \\ \sqrt{h_{y,t}} \end{bmatrix}$, $\varepsilon_t = \begin{bmatrix} \varepsilon_{x,t} \\ \varepsilon_{y,t} \end{bmatrix}$, $C = \begin{bmatrix} c_{11} & c_{12} \\ 0 & c_{22} \end{bmatrix}$, $A = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}$, $B = \begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix}$, and Ω_{t-1} is the information set at t^{th} time point. The maximum likelihood method has been employed to estimate the VAR-GARCH-M model under the condition that the conditional variance–covariance matrix, i.e., H_t is positive definite for all sample values of ε_t. We have adopted Grier et al.'s (2004) BEKK GARCH model[6] to specify H_t, which is a positive definite matrix by construction. The diagonal elements $h_{x,t}$ and $h_{y,t}$ in H_t represent the conditional variances of inflation and output growth, respectively, while $h_{xy,t}$ (or $h_{yx,t}$) represents the conditional covariance between inflation and growth. In accordance with the majority of empirical studies on uncertainty, we have considered the conditional standard deviations of inflation ($\sqrt{h_{x,t}}$) and output growth ($\sqrt{h_{y,t}}$) as the measures of nominal and real uncertainty, respectively. The estimates of $\sqrt{h_{x,t}}$ and $\sqrt{h_{y,t}}$ have been incorporated into the mean equation through the 'in-mean' coefficient matrix Γ. The 'in-mean' parameters γ_{11}, γ_{21}, γ_{12} and γ_{22} hypothesize the effects of nominal uncertainty on inflation and output growth and real uncertainty on inflation and output growth, respectively. In Eq. (1), the parameter $\psi_{i,11}$ ($\psi_{i,22}$) denotes the ith order own

[6] In the literature, the diagonal CCC (constant conditional correlation) of Bollerslev (1990) and the BEKK model of Engle and Kroner (1995) are frequently used to measure macroeconomic uncertainties in a bivariate framework (Grier et al. 2004; Bredin and Fountas 2005, 2009; Shields et al. 2005; Fountas et al. 2006; Bhar and Mallik 2010; Conrad and Karanasos 2010).

lag effect of inflation (output growth), whereas $\psi_{i,12}$ $(\psi_{i,21})$ indicates the ith lag effect of output growth on inflation (inflation on output growth).

Similar to its univariate counterpart, the bivariate GARCH model has one limitation: it provides symmetric responses to positive and negative shocks of equal magnitude. In their study, Shields et al. (2005) argue that volatility models of inflation and output growth must account for the differential effects associated with the sign of the past shocks; failing to do so may result in an inaccurate estimation of conditional variances and their impacts on economic performance. Grier et al. (2004) and Shields et al. (2005) proposed a threshold GARCH model in a bivariate framework to incorporate the concepts of 'good' and 'bad' news of inflation and output growth in order to introduce asymmetry in the variance–covariance processes. The 'bad' news of inflation is implied when inflation is higher than expected and is indicated by the positive inflation residuals. In contrast, the positive residuals in output growth indicate 'good' news regarding growth. According to Grier et al. (2004) and Shields et al. (2005), the following is the asymmetric version of the BEKK GARCH specification:

$$H_t = CC' + A\varepsilon_{t-1}\varepsilon_{t-1}{}'A' + Du_{t-1}u_{t-1}{}'D' + BH_{t-1}B' \tag{3}$$

where $D = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}$, $u_{t-1} = \begin{bmatrix} u_{x,t-1} \\ u_{y,t-1} \end{bmatrix}$ and $u_{x,t-1} = \varepsilon_{x,t-1}I\left(\varepsilon_{x,t-1} \le 0\right)$, $u_{y,t-1} = \varepsilon_{y,t-1}I\left(\varepsilon_{y,t-1} \le 0\right)$. $I\left(\varepsilon_{x,t-1} \le 0\right)$ is an indicator function of inflation which returns 1 if $\varepsilon_{x,t-1} \le 0$, and 0 otherwise. Similarly, in case of output growth, $I\left(\varepsilon_{y,t-1} \le 0\right)$ is 1 when $\varepsilon_{y,t-1} \le 0$, and 0 otherwise. Together, Eqs. (1) and (3) constitute the VAR-AGARCH-M model.

Following Neanidis and Savva (2013) and Chowdhury et al. (2018), we propose a self-exciting threshold VAR (SETVAR) model for inflation and output growth. The model allows the causal linkages to vary with the level of inflation and output growth. The first lagged values of inflation and output growth are considered as the threshold variables that separate the regimes into 'low' (l) and 'high' (h). The threshold values of inflation and output growth are assumed to be exogenous and taken to be their average values, denoted by $\overline{x}$ and $\overline{y}$, respectively. According to Hartmann and Roestel (2013), the average values of inflation and output growth can reflect the reliability and usefulness of the monetary authority's decisions in anchoring inflation and economic growth. Moreover, different average values for various countries reflect inherent country-specific heterogeneity, allowing us to assess its significance in determining the causal links between macroeconomic performance and their uncertainties. In addition, the statistical inference of the threshold model would not be affected by *nuisance parameters* because the threshold values are chosen exogenously (Franses and Van Dijk 2000). The use of known threshold values also reduces the computational burden of estimation. The SETVAR model is characterized by the following:

$$\begin{aligned} Z_t = &\left(\left(\mu^l + \Psi_1^l Z_{t-1} + \Psi_2^l Z_{t-2} + \cdots + \Psi_p^l Z_{t-p} + \Gamma^l \sqrt{h_t}\right) \odot (\boldsymbol{I}[\cdot])\right) \\ &+ \left(\left(\mu^h + \Psi_1^h Z_{t-1} + \Psi_2^h Z_{t-2} + \cdots + \Psi_p^h Z_{t-p} + \Gamma^h \sqrt{h_t}\right) \odot (1 - \boldsymbol{I}[\cdot])\right) + \varepsilon_t \end{aligned} \tag{4}$$

where $\mu^j = \begin{bmatrix} \mu_1^j \\ \mu_2^j \end{bmatrix}$, $\Psi_i^j = \begin{bmatrix} \psi_{i,11}^j & \psi_{i,12}^j \\ \psi_{i,21}^j & \psi_{i,22}^j \end{bmatrix}$, $\Gamma^j = \begin{bmatrix} \gamma_{11}^j & \gamma_{12}^j \\ \gamma_{21}^j & \gamma_{22}^j \end{bmatrix}$ for $j = l, h$ and $i = 1, 2, \ldots, p$. Further, $\mathbf{1} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$, $\boldsymbol{I}[\cdot] = \begin{bmatrix} \mathrm{I}(x_{t-1} \leq \overline{x}) \\ \mathrm{I}(y_{t-1} \leq \overline{y}) \end{bmatrix}'$, and $\mathrm{I}(x_{t-1} \leq \overline{x})$ is an indicator function that takes the value 1 if $(x_{t-1} \leq \overline{x})$ and 0 otherwise. Similar interpretation applies to $\mathrm{I}(y_{t-1} \leq \overline{y})$. The symbol $\odot$ denotes the Hadamard product of matrices. The SETVAR-AGARCH-M model consists of the conditional mean, as specified in Eq. (4), and the conditional variance–covariance matrix, H_t, as shown in Eq. (3). All the models were estimated using the maximum likelihood estimation (MLE) method. Further, the standard errors of the estimates have been corrected through Bollerslev and Wooldridge's (1992) method to make them robust to non-normal errors. We have adopted the BFGS algorithm for optimization of the likelihood function and used a series of initial coefficients values to ensure the estimation procedure converged to a global maximum.

3.1 Selection of model and specification tests on GARCH parameters

Since the models (VAR-GARCH-M, VAR-AGARCH-M, and SETVAR-AGARCH-M) are parametrically nested,[7] the likelihood ratio (LR) test can be carried out to select an appropriate model for each country in the sample. The LR test is defined as $\mathrm{LR} = -2(\mathrm{L}(\Phi_0) - \mathrm{L}(\Phi_1)$, where Φ_0 and Φ_1, $\mathrm{L}(\Phi_0)$ and $\mathrm{L}(\Phi_1)$ are the parameter sets and the log likelihood values of two competing models, respectively. The test statistic follows a χ^2 distribution with k degrees of freedom where k denotes the number of restrictions. We choose three pairs of models, viz., VAR-GARCH-M and VAR-AGARCH-M, VAR-GARCH-M and SETVAR-AGARCH-M, and VAR-AGARCH-M and SETVAR-AGARCH-M, and then apply LR tests to determine the most appropriate model for a country. After the model has been chosen, a number of specification tests involving (A)GARCH parameters are considered [see Grier et al. (2004) and Bredin and Fountas (2009)]. We begin with the 'no-GARCH' test, which requires that all the coefficients, namely α_{ij}, β_{ij} for $i, j = 1, 2$ in case of GARCH and α_{ij}, β_{ij}, d_{ij} for AGARCH be jointly insignificant. Given the GARCH effect, one may wish to examine the volatility spillover between inflation and growth. Such a spillover effect would imply a non-diagonal variance–covariance process. The test for 'diagonal GARCH' therefore requires that the off-diagonal elements of the matrices A and B (for GARCH)/A, B, and D(for AGARCH) are jointly insignificant. Finally, we consider the null hypothesis of 'no asymmetric effect', which is defined as $H_0 : d_{11} = d_{12} = d_{21} = d_{22} = 0$. Rejection of H_0 implies that the negative and positive shocks have different effects on uncertainty. In this context, it should be noted that as the BEKK version of the GARCH/AGARCH model is by design positive definite, the direct effect of output growth uncertainty (inflation uncertainty) on inflation uncertainty (output growth uncertainty), if present, will always be positive. We can therefore only test for the presence or absence of a spillover effect. We can at best determine whether the

[7] SETVAR-AGARCH-M nests both VAR-GARCH-M and VAR-AGARCH-M, whereas VAR-GARCH-M is nested in VAR-AGARCH-M.

effect is unidirectional or bidirectional. The same holds true for the asymmetric effects of past shocks, so if the asymmetric effect is significant, a negative shock will always have a positive effect on uncertainty.[8]

4 Results

We have taken monthly data on the index of industrial production (IIP) and consumer price index (CPI) to measure output and price levels for 19 countries,[9] namely Brazil, Malaysia, the Philippines, Austria, Denmark, Belgium, Ireland, Greece, Norway, Spain, Portugal, Sweden, the UK, the USA, Barbados, Chile, Israel, Jordan, and South Africa.[10] The data of all the above countries were collected from the CEIC website (https://www.ceicdata.com). For all countries except Brazil, the Philippines, Barbados, Chile, and Jordan, the data span January 1990 to December 2017.[11] All the series are seasonally adjusted through the Tramo/Seats method. Inflation is denoted by x_t and defined as $x_t = \log(\mathrm{CPI_t}/\mathrm{CPI_{t-1}}) * 100$. Similarly, output growth (y_t) is defined as $y_t = \log(\mathrm{IIP_t}/\mathrm{IIP_{t-1}}) * 100$.

According to summary statistics (Table 1), monthly average inflation rates in the majority of countries are low, ranging from 0.10 to 0.30%. The monthly range is equivalent to annual inflation rates between 1 and 4%. The evidence of low inflation rates indicates that most of the sampled countries have successfully pursued price stabilization policies over the past two and a half decades. Few countries, including Brazil, the Philippines, Greece, Israel, and South Africa, have monthly inflation rates of 0.40 percent or higher. The ADF test was conducted to determine whether the inflation rates were stationarity or non-stationarity. It has been argued (Hartmann and Roestel 2013) that a country's inflation rate is expected to be stationary if its steady-state inflation rate does not change substantially over a sample period. In our case, the results of the ADF test indicate that the inflation series for all countries are stationary,

[8] By expanding Eq. (3), we obtain the following specification for the conditional variance of inflation $h_{x,t} = c_{11}^2 + c_{12}^2 + \alpha_{11}^2\varepsilon_{x,t-1}^2 + 2\alpha_{11}\alpha_{12}\varepsilon_{x,t-1}\varepsilon_{y,t-1} + \alpha_{12}^2\varepsilon_{y,t-1}^2 + \beta_{11}^2 h_{x,t-1} + 2\beta_{11}\beta_{12}h_{xy,t-1} + \beta_{12}^2 h_{y,t-1} + d_{11}^2 u_{x,t-1}^2 + 2d_{11}d_{12}u_{x,t-1}u_{y,t-1} + d_{12}^2 u_{y,t-1}^2$.The conditional variance of output growth can be specified in a similar way. It is worth noting that the direct effect of real uncertainty on nominal uncertainty (indicated by α_{12}^2, β_{12}^2, and d_{12}^2) is positive. The coefficient d_{11}^2 also indicate that the asymmetric effect of negative shocks in inflation on inflation uncertainty is positive.

[9] Our selection of countries is based on Hartmann and Roestel's (2013) list. Although their study included 34 countries, in our work we only consider those countries for which all the models mentioned in Sect. 3 converge and yield estimation results.

[10] Among this group, some countries like Brazil, the Philippines, Norway, Spain, Sweden, the UK, the USA, Chile, Israel, and South Africa are inflation targeters, and the rest are non-inflation targeters. Although non-targeting countries lack an explicit inflation target, they frequently announce a desired level of inflation and periodically evaluate monetary policies in pursuit of price stability. For instance, the European Central Bank (ECB) does not consider itself an inflation targeting-central bank; however, since the inception of the euro in 1999, it has set a desired inflation rate of 2% or less for all euro area countries.

[11] According to data availability, the beginning and ending dates for the Philippines, Barbados, Chile, and Jordan are January 1993 and December 2017, January 1990 and October 2014, January 1997 and December 2017, and January 1997 and December 2017, respectively. In Brazil, we have chosen January 1995 as the starting point, thus excluding the hyperinflationary periods of the first half of the 1990s.

Table 1 Descriptive statistics and unit roots test of inflation and output growth

	Inflation				Output growth			
	Mean	Kurtosis	Normality	ADF test	Mean	Kurtosis	Normality	ADF test
Brazil	0.57	8.43	[0.00]	– 6.77***	0.07	15.57	[0.00]	– 18.58***
Malaysia	0.23	2.85	[0.00]	– 13.84***	0.44	4.48	[0.00]	– 25.65***
The Philippines	0.39	10.27	[0.00]	– 11.31***	0.25	6.18	[0.00]	– 23.09***
Austria	0.17	3.47	[0.00]	– 7.65***	0.25	12.31	[0.00]	– 19.16***
Belgium	0.17	3.66	[0.00]	– 15.04***	0.15	4.75	[0.00]	– 19.14***
Denmark	0.15	4.86	[0.00]	– 16.23***	0.07	5.58	[0.00]	– 15.35***
Greece	0.40	8.76	[0.00]	– 3.80***	– 0.03	9.38	[0.00]	– 15.34***
Ireland	0.17	9.42	[0.00]	– 5.95***	0.59	7.01	[0.00]	– 5.18***
Norway	0.18	16.30	[0.00]	– 14.84***	0.05	5.31	[0.00]	– 15.97***
Portugal	0.27	5.73	[0.00]	– 3.56***	0.03	4.23	[0.00]	– 19.20***
Spain	0.23	4.31	[0.00]	– 5.50***	0.02	5.46	[0.00]	– 4.74***
Sweden	0.15	25.29	[0.00]	– 15.32***	0.13	4.13	[0.00]	– 24.21***
The UK	0.21	18.59	[0.00]	– 7.32***	0.01	6.45	[0.00]	– 21.92***
The USA	0.20	12.26	[0.00]	– 11.44***	0.15	12.43	[0.00]	– 4.90***
Barbados	0.29	29.93	[0.00]	– 15.57***	– 0.02	7.68	[0.00]	– 13.56***
Chile	0.27	4.53	[0.00]	– 10.03***	0.15	4.96	[0.00]	– 15.92***
Israel	0.38	4.74	[0.00]	– 7.86***	0.33	4.20	[0.00]	– 17.62***
Jordan	0.26	19.96	[0.00]	– 12.66***	0.20	8.41	[0.00]	– 17.48***
South Africa	0.55	4.05	[0.00]	– 4.37***	0.10	4.61	[0.00]	– 10.77***

The number in square brackets are *p*-values. *** indicates significance at 1% significance level thereby validating the argument that the average inflation rates in these countries have not changed significantly during the sample periods.

It has been well documented that during the 1990s, output growth volatility decreased significantly in many countries (Cecchetti and Krause 2001; Bernanke 2004; Stock and Watson 2003, 2005). Nevertheless, during the period 2000–2007, a number of developed countries experienced a decline in total factor productivity accompanied by sluggish investment. The situation has worsened since the financial crisis in 2008, resulting in a significant decline in the trend growth rates of these countries (Ollivaud et al. 2016). This phenomenon is reflected in summary statistics, where most countries exhibit low monthly average growth rates. It is important to note that the distinction between 'high' and 'low' growth regimes can be linked to the expansion and contraction phases of these economies. According to the ADF test, output growth is stationary in all countries. Finally, both inflation and output growth have high kurtosis values, and Bera-Jarque's test indicates that the series are not normally distributed.

For selecting an appropriate model between VAR-GARCH-M, VAR-AGARCH-M, and SETVAR-AGARCH-M, we first identify the optimal lag order in the VAR-GARCH-M model for each of the nineteen countries. In the subsequent analyses, we will use the same lag values for the other two models. The Hannan-Quinn criterion (HQC) has been used to determine p. Optimum lag values were found to be 1 in the Philippines, 2 in Malaysia, Austria, Belgium, Norway, Chile, Israel, and Jordan, 3 in Denmark, Portugal, the UK, the USA, and Barbados, 4 in Greece, Ireland, and Sweden, 5 in Brazil, and 6 in Spain and South Africa.[12]

The likelihood ratio (LR) test is then utilized to select the optimal model. In Table 2, we present the maximum log likelihood values for the three models, followed by the results of the LR test. The appropriate model for each country is reported in the last column of the table. In the case of Brazil for instance, the maximized log likelihood values for the VAR-GARCH-M, VAR-AGARCH-M, and SETVAR-AGARCH-M models are -535.81, -528.10, and -527.39, respectively. The LR test statistic for comparing VAR-GARCH-M and VAR-AGARCH-M is 15.42 and significant at the 1% significance level, thus favouring VAR-AGARCH-M over the VAR-GARCH-M model. However, the test result indicates that there is no significant difference between the log-likelihood values of the VAR-AGARCH-M and the SETVAR-AGARCH-M models. Therefore, the VAR-AGARCH-M model is the optimal model for Brazil. The optimal model for Belgium, Denmark, and Israel is VAR-GARCH-M; for Brazil, the Philippines, and Norway, it is VAR-AGARCH-M; and for the remaining countries, it is SETVAR-AGARCH-M.

4.1 Estimation results of the VAR-GARCH/AGARCH-M model

It is noted from Table 2 that the optimal model for six countries, namely Belgium, Denmark, Israel, Brazil, the Philippines, and Norway, is VAR-GARCH/AGARCH-M, indicating that the inflation-growth-uncertainty relationships in these countries do not vary with inflation and output growth levels. In Table 3, we report the estimates of some

[12] In order to reduce the computational burden, the search for an optimal p was limited to lags from 1 to 8 for all countries. The results are available on request.

Table 2 Selection of an appropriate model

	Maximum log-likelihood value			LR test			Appropriate model
	Model I	Model II	Model III	Model I vs Model II	Model I vs Model III	Model II vs Model III	
Belgium	− 720.12	− 718.62	− 708.04	3.00	24.16	21.16	VAR-GARCH-M
Denmark	− 670.27	− 668.58	− 659.28	3.38	21.98	18.60	VAR-GARCH-M
Israel	− 890.81	− 890.72	− 883.45	0.18	14.72	14.54	VAR-GARCH-M
Brazil	− 535.81	− 528.10	− 527.39	15.42***	16.84	1.42	VAR-AGARCH-M
The Philippines	− 933.67	− 928.83	− 927.15	9.68**	13.04	3.36	VAR-AGARCH-M
Norway	− 815.32	− 807.82	− 797.76	15.00***	35.12***	20.12	VAR-AGARCH-M
Malaysia	− 810.88	− 801.14	− 778.72	19.48***	64.32***	44.84***	SETVAR-AGARCH-M
Austria	− 293.79	− 283.29	− 262.65	21.00***	62.88***	41.28***	SETVAR-AGARCH-M
Greece	− 837.96	− 827.68	− 807.35	20.56***	61.22***	40.66***	SETVAR-AGARCH-M
Ireland	− 866.99	− 865.59	− 841.07	2.80	51.84***	49.04***	SETVAR-AGARCH-M
Portugal	− 637.06	− 635.19	− 617.14	3.74	39.84**	36.10***	SETVAR-AGARCH-M
Spain	− 382.54	− 373.34	− 353.08	18.40***	58.92***	40.52*	SETVAR-AGARCH-M
Sweden	− 664.25	− 655.86	− 633.52	18.12***	61.46***	44.68***	SETVAR-AGARCH-M
the UK	− 206.07	− 205.78	− 185.11	0.58	41.92***	41.34***	SETVAR-AGARCH-M
the USA	− 175.13	− 164.21	− 137.76	21.84***	74.74***	52.90***	SETVAR-AGARCH-M
Barbados	− 901.93	− 895.65	− 863.03	12.56**	77.8***	65.24***	SETVAR-AGARCH-M
Chile	− 580.80	− 580.74	− 567.85	0.12	25.9*	25.78**	SETVAR-AGARCH-M
Jordan	− 916.50	− 916.15	− 879.13	0.70	74.74***	74.04***	SETVAR-AGARCH-M
South Africa	− 657.44	− 657.13	− 627.22	0.62	60.44***	59.82***	SETVAR-AGARCH-M

Model I VAR-GARCH-M, *Model II* VAR-AGARCH-M, *Model III* SETVAR-AGARCH-M

***,**,*indicate the significance at 1%, 5%, and 10% levels of significance, respectively

Table 3 Results of the VAR-GARCH/AGARCH-M model

	Belgium	Denmark	Israel	Brazil	The Philippines	Norway
Panel A						
'In-mean' coefficients						
γ_{11}	− 0.821*	2.383	2.192***	1.053**	1.846***	− 0.294
	(0.454)	(1.805)	(0.573)	(0.437)	(0.488)	(0.179)
γ_{21}	− 3.030	0.328	2.772	1.254	− 4.409	0.726
	(4.530)	(7.254)	(2.076)	(1.944)	(4.781)	(1.688)
γ_{12}	− 0.043	0.014	0.122	− 0.059**	− 0.001	− 0.010
	(0.035)	(0.015)	(0.093)	(0.027)	(0.016)	(0.019)
γ_{22}	0.680	0.390	0.183	− 0.145	0.649	1.075
	(0.609)	(0.349)	(0.401)	(0.376)	(0.400)	(0.712)
Bidirectional causal relationships between inflation and growth						
$y \nrightarrow x$	0.871	2.825	4.870	25.218***	0.000	1.018
	[0.65]	[0.42]	[0.10]	{-}[0.00]	[0.93]	[0.60]
$x \nrightarrow y$	0.604	13.478***	0.908	6.955	0.247	1.794
	[0.74]	{ +} [0.00]	[0.64]	[0.22]	[0.68]	[0.41]
Panel B						
No GARCH	4760.75***	374,796.65***	1,028,716.85***	23,964.53***	9,528,291.99***	3777.90***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Diagonal GARCH	6.16	6.77	3.302	43.07***	5.01	22.19***
	[0.19]	[0.15]	[0.51]	[0.00]	[0.54]	[0.00]
No asymmetric GARCH	– -	– -	– -	83.11***	25.72***	10.87**

Table 3 (continued)

	Belgium	Denmark	Israel	Brazil	The Philippines	Norway
				[0.00]	[0.00]	[0.04]
Volatility spillover coefficients						
α_{12}	--	--	--	[0.64]	--	[0.02]**
d_{12}	--	--	--	[0.95]	--	[0.49]
β_{12}	--	--	--	[0.07]*	--	[0.05]***
α_{21}	--	--	--	[0.48]	--	[0.94]
d_{21}	--	--	--	[0.03]**	--	[0.22]
β_{21}	--	--	--	[0.23]	--	[0.73]
Asymmetric GARCH coefficients						
d_{11}	--	--	--	[0.00]***	[0.71]	[0.89]
d_{22}	--	--	--	[0.07]*	[0.00]***	[0.00]***

γ_{11}, impact of nominal uncertainty on inflation; γ_{21}, impact of nominal uncertainty on output growth; γ_{12}, impact of real uncertainty on inflation; γ_{22}, effect of real uncertainty on output growth; $y \nrightarrow x$, output growth does not Granger cause inflation; $x \nrightarrow y$, inflation does not Granger cause output growth; d_{11}, effect of negative shocks in inflation on nominal uncertainty; d_{22}, effect of negative shocks in output growth on real uncertainty. The sign in {} represents the sign of the sum of the lag coefficients, the number in square brackets are p-values, ***,**,*Indicate the significance at 1, 5 and 10% significance levels, respectively. Standard errors (Bollerslev and Wooldridge 1992) are reported in ()

relevant parameters of the VAR-GARCH/AGARCH-M model. It is observed that for four nations, namely Belgium, Brazil, the Philippines, and Israel, nominal uncertainty has a significant impact on inflation. In the case of Belgium, the effect is negative, while in Denmark and Norway, it is insignificant. This finding supports the effectiveness of price stabilization policies in these countries. It is noted, however, that the coefficient is positive and significant in three high-inflation economies, namely Israel, Brazil, and the Philippines, suggesting that inflation uncertainty increases inflation in these countries. As for Brazil, our finding is similar to that of Ferreira and Palma (2016), who found that inflation uncertainty has a time-invariant positive impact on inflation. In the case of the Philippines, the positive effect is in accordance with the findings of Jiranyakul and Opiela (2010). Despite the fact that all these three countries explicitly targeted inflation, the positive association between inflation uncertainty and inflation raises concerns about the effectiveness of their inflation targeting policies.

Further, we find no statistical support for the other three 'in-mean' effects (i.e., the effects of nominal uncertainty on output growth, real uncertainty on inflation and output growth). In almost all cases, estimates are insignificant. Moreover, the Granger-causality tests on the parameters $\psi_{i,12}$ and $\psi_{i,21}$ (for $i = 1, 2, \ldots, p$) reveal a lack of a bi-directional relationship between output growth and inflation.

4.2 Estimation results of the SETVAR-AGARCH-M model

According to the results in Table 2, thirteen countries in our sample favour the regime-dependent model. The estimation results of the SETVAR-AGARCH-M model for all 13 countries are reported in Table 4. Regarding the 'in-mean' effects, the following findings are made. We obtain that in Malaysia, Sweden, Barbados, Jordan, and South Africa, inflation uncertainty has a regime-dependent effect on inflation, whereas the remaining countries exhibit no support of the relationship. In Malaysia, nominal uncertainty reduces inflation irrespective of the inflation regime. However, the magnitude of the effect doubles in the high-inflation regime compared to the low-inflation regime. Sweden and Barbados exhibit significant negative effects only during high inflation periods, thereby supporting Holland's (1995) stabilization hypothesis. In case of the USA, our result is consistent with Chang (2012), who demonstrated that nominal uncertainty has no significant effect on inflation during less volatile periods of inflation. In addition, the countries from the euro area do not exhibit any significant causal relationships between these two variables, indicating that the common monetary policies have been effective in achieving price stability in these countries. In contrast, in two developing countries, like Jordan and South Africa, nominal uncertainty leads to an increase in inflation. Based on the results, it appears that the inflation targeting policies were not as effective in South Africa as they were in the other developed countries. In general, the results indicate that the impact of nominal uncertainty on inflation, if it exists, is more pronounced in high inflation regimes than in low inflation regimes. In addition, the effectiveness of monetary policy may vary from country to country depending on their specific economic conditions and institutional frameworks. In countries such as Greece, Spain, Sweden, the UK, the USA, and Jordan, nominal uncertainty affects output growth significantly in at least one output growth regime.

Table 4 Results of the SETVAR-AGARCH-M model

	Malaysia	Austria	Greece	Ireland	Portugal	Spain	Sweden
Panel A							
'In-mean' coefficients							
γ_{11}^{l}	− 0.515***	7.277	− 2.000	0.120	0.461	0.040	− 0.338
	(0.118)	(9.744)	(1.888)	(0.093)	(0.795)	(0.777)	(0.284)
γ_{11}^{h}	− 1.265***	− 10.976	− 1.207	− 0.067	− 0.247	− 0.018	− 0.842**
	(0.268)	(8.405)	(2.174)	(0.164)	(0.607)	(0.547)	(0.349)
γ_{21}^{l}	0.347	32.978	37.122*	− 2.352	− 1.656	− 2.187	− 2.152**
	(0.531)	(33.019)	(19.253)	(1.542)	(2.339)	(2.719)	(1.022)
γ_{21}^{h}	1.138	− 44.100	12.028	− 1.398	6.290	− 6.003**	− 1.726**
	(0.820)	(36.335)	(17.106)	(4.928)	(4.684)	(2.992)	(0.749)
γ_{12}^{l}	− 0.084**	− 0.164**	− 0.038	− 0.011***	0.037	0.027	0.005
	(0.041)	(0.077)	(0.286)	(0.003)	(0.123)	(0.032)	(0.034)
γ_{12}^{h}	0.027*	0.109	0.721	0.026	− 0.140	0.035	− 0.042
	(0.014)	(0.178)	(0.447)	(0.029)	(0.112)	(0.033)	(0.033)
γ_{22}^{l}	− 0.228	− 1.401**	− 5.027**	− 0.612**	0.665	− 0.605	− 0.811*
	(0.804)	(0.557)	(2.328)	(0.275)	(1.191)	(0.629)	(0.435)
γ_{22}^{h}	− 1.816	0.843	− 1.829	0.019	− 0.999	− 0.620	− 0.267
	(1.232)	(0.902)	(1.955)	(0.567)	(1.377)	(0.545)	(0.393)
Bidirectional causal relationships between inflation and growth							
$TGC\ (y \nrightarrow x)$	3.709	6.096	10.385	53.834***	9.086	23.208**	4.885
	[0.45]	[0.19]	[0.24]	[0.00]	[0.17]	[0.03]	[0.77]

Table 4 (continued)

	Malaysia	Austria	Greece	Ireland	Portugal	Spain	Sweden
$y \nrightarrow x(low)$				9.038*		4.801	
				{ +} [0.06]		[0.57]	
$y \nrightarrow x(high)$				51.836***		15.714**	
				{ +} [0.00]		{ +} [0.02]	
$TGC\ (x \nrightarrow y)$	7.838*	2.316	5.563	14.568	11.549*	16.197	21.828**
	[0.09]	[0.68]	[0.70]	[0.10]	[0.07]	[0.18]	[0.01]
$x \nrightarrow y(low)$	0.926				10.571**		15.265***
	[0.63]				{-} [0.01]		{ +} [0.00]
$x \nrightarrow y(high)$	6.033**				0.223		7.231
	{-} [0.04]				[0.97]		[0.12]
Panel B							
No GARCH	170.69***	659.06***	268,782.04***	40,543.69***	439.84***	431.87***	1306.81***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]
Diagonal GARCH	18.67**	182.74***	2158.72***	9.64	59.89***	19.25***	12.03*
	[0.01]	[0.00]	[0.00]	[0.14]	[0.00]	[0.00]	[0.06]
No asymmetric GARCH	31.89***	9.41*	19.68***	5.65	7.88*	13.60**	36.01***
	[0.00]	[0.05]	[0.00]	[0.23]	[0.09]	[0.01]	[0.00]
Volatility spillover coefficients							
α_{12}	[0.15]	[0.12]	[0.43]	--	[0.13]	[0.00]*	[0.02]**
d_{12}	[0.45]	[0.71]	[0.00]***	--	[0.78]	[0.28]	[0.41]
β_{12}	[0.00]***	[0.04]**	[0.00]***	--	[0.00]*	[0.01]**	[0.60]

Table 4 (continued)

	Malaysia	Austria	Greece	Ireland	Portugal	Spain	Sweden
α_{21}	[0.07]*	[0.20]	[0.00]***	--	[0.70]	[0.88]	[0.93]
d_{21}	[0.82]	[0.52]	[0.06]*	--	[0.72]	[0.73]	[0.07]*
β_{21}	[0.40]	[0.00]***	[0.00]***	--	[0.37]	[0.78]	[0.90]
Asymmetric GARCH coefficients							
d_{11}	[0.03]**	[0.28]	[0.54]	--	[0.69]	[0.03]**	[0.19]
d_{22}	[0.00]***	[0.01]**	[0.43]	--	[0.08]*	[0.00]*	[0.00]*

	The UK	The USA	Barbados	Chile	Jordan	South Africa
Panel A						
'In-mean' coefficients						
γ_{11}^{l}	0.171	0.798	− 0.099	− 0.514	0.024	− 0.892
	(0.481)	(0.766)	(0.272)	(0.614)	(0.321)	(0.824)
γ_{11}^{h}	1.415	0.534	− 1.464***	− 0.042	3.662***	2.405**
	(0.884)	(0.369)	(0.351)	(0.489)	(0.712)	(1.004)
γ_{21}^{l}	− 4.305*	− 2.313***	− 0.457	0.966	− 6.882***	0.459
	(2.271)	(0.805)	(0.721)	(1.876)	(1.77)	(4.139)
γ_{21}^{h}	4.097	− 0.523	− 0.640	− 0.325	− 3.666	0.357
	(2.588)	(0.570)	(1.324)	(2.124)	(2.586)	(4.023)
γ_{12}^{l}	− 0.016	− 0.365	0.179	0.037	− 0.066	− 0.033
	(0.037)	(0.266)	(0.116)	(0.061)	(0.069)	(0.072)
γ_{12}^{h}	− 0.027	− 0.183	0.410***	− 0.054	− 0.831***	− 0.058

Table 4 (continued)

	The UK	The USA	Barbados	Chile	Jordan	South Africa
	(0.058)	(0.214)	(0.132)	(0.069)	(0.214)	(0.096)
γ_{22}^{l}	0.063	2.908***	0.031	3.302**	1.321**	− 0.481
	(0.255)	(1.020)	(0.461)	(1.380)	(0.494)	(1.725)
γ_{22}^{h}	− 2.767***	0.536	− 2.168	− 1.590	0.647	− 1.524
	(0.838)	(0.903)	(1.456)	(1.861)	(0.581)	(2.453)
Bidirectional causal relationships between inflation and growth						
TGC ($y \nrightarrow x$)	9.426	6.344	33.688***	6.285	111.72***	20.060*
	[0.15]	[0.39]	[0.00]	[0.18]	[0.00]	[0.07]
$y \nrightarrow x(low)$			5.566		27.412***	3.190
			[0.14]		{ +} [0.00]	[0.79]
$y \nrightarrow x(high)$			30.606***		15.559***	11.377*
			{ +} [0.00]		{ +} [0.00]	{ +} [0.08]
TGC ($x \nrightarrow y$)	17.218**	19.343***	41.708***	25.289***	34.552***	12.136
	[0.01]	[0.00]	[0.00]	[0.00]	[0.00]	[0.44]
$x \nrightarrow y(low)$	0.666	17.204***	2.680	5.202*	27.291***	
	[0.24]	{ +} [0.00]	[0.44]	{-} [0.07]	{ +} [0.00]	
$x \nrightarrow y(high)$	15.956***	1.746	27.749***	16.438***	9.185**	
	{-} [0.00]	[0.63]	{-} [0.00]	{-} [0.00]	{ +} [0.00]	
Panel B						
No GARCH	39,135.77***	1582.20***	120.52***	2004.82***	7724.61***	3078.69***
	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]	[0.00]

Table 4 (continued)

	The UK	The USA	Barbados	Chile	Jordan	South Africa
Diagonal GARCH	47.65***	21.50***	41.87***	1.127	455.08***	22.33***
	[0.00]	[0.00]	[0.00]	[0.98]	[0.00]	[0.00]
No asymmetric GARCH	4.19	10.16**	32.08***	8.448*	61.61***	0.005
	[0.38]	[0.04]	[0.00]	[0.08]	[0.00]	[0.99]
Volatility spillover coefficients						
α_{12}	[0.74]	[0.05]*	[0.00]***	--	[0.00]***	[0.13]
d_{12}	[0.77]	[0.07]*	[0.08]*	--	[0.72]	[0.99]
β_{12}	[0.46]	[0.83]	[0.56]	--	[0.00]***	[0.02]**
α_{21}	[0.00]***	[0.12]	[0.76]	--	[0.29]	[0.94]
d_{21}	[0.55]	[0.10]	[0.09]*	--	[0.00]***	[0.99]
β_{21}	[0.07]*	[0.26]	[0.31]	--	[0.00]***	[0.78]
Asymmetric GARCH coefficients						
d_{11}	--	[0.85]	[0.43]	[0.68]	[0.19]	--
d_{22}	--	[0.60]	[0.00]***	[0.01]**	[0.00]***	--

γ_{11}^{l} and γ_{11}^{h} indicate the effects of nominal uncertainty on inflation in low- and high-inflation regimes, respectively, γ_{21}^{l} and γ_{21}^{h} denote the impacts of nominal uncertainty on output growth in low-and high-output growth regimes, respectively, γ_{12}^{l} and γ_{12}^{h}: effects of output growth uncertainty on inflation during low- and high- inflation regimes, respectively, γ_{22}^{l} and γ_{22}^{h} denote the influences of real uncertainty on output growth in low- and high-growth regimes, respectively, TGC: threshold Granger causality test (Li 2006), $y \nrightarrow x(low)$ and $y \nrightarrow x(high)$: output growth do not Granger cause inflation in low- and high-inflation regimes, repectively, $x \nrightarrow y(low)$: inflation does not Granger cause output growth in low-growth regime, $x \nrightarrow y(high)$: inflation does not Granger cause output growth in high-growth regime, d_{11}: effect of negative shocks in inflation on inflation uncertainty, and d_{22}: effect of negative shocks in output growth on growth uncertainty. The sign in {} represents the sign of the sum of the lag coefficients, the number in square brackets are p-values, ***,**,*indicate the significance at 1, 5 and 10% significance levels, respectively. Standard errors (Bollerslev and Wooldridge 1992) are reported in ()

Particularly, in the cases of Sweden, the UK, the USA, and Jordan, nominal uncertainty has a negative effect on output growth during periods of economic contraction, whereas the impact becomes insignificant or remains negative during periods of high growth. Our findings for the UK and the USA are in line with those of Chowdhury et al. (2018) and Caglayan et al. (2015), who found that nominal uncertainty had a greater negative impact on output growth during economic downturns. The dominance of the negative influence in the low growth regime is consistent with the argument of Bloom (2009) and Caggiano et al. (2020), which states that higher uncertainty in periods of economic contraction adversely affects firms' investment decisions in hiring productive inputs, resulting in lower economic activity and, in turn, lower output growth. Moreover, the negative impact of uncertainty on investment decisions may also spill over to consumer behaviour, as households may become more cautious in their spending habits due to concerns about future economic prospects. This can further prolong the low growth regime. The coefficients, γ_{12}^{l} and γ_{12}^{h} denote the effects of real uncertainty on inflation in low and high inflation regimes, respectively. Most countries, with the exception of Malaysia, Austria, Ireland, Barbados, and Jordan, do not possess a significant relationship between these two variables.

We obtain substantial evidence in support of the regime-dependent effects of output growth volatility on output growth in eight countries. Importantly, the relationship is detected only in low growth regimes in each country, except the UK. In countries like Austria, Greece, Ireland, the UK, and Sweden, real uncertainty adversely affects output growth. This finding is consistent with the argument of Bernanke (1983), and Pindyck (1991), which suggests that greater variability in output growth leads to unanticipated changes in growth rates and generates greater uncertainty in the future demand for firms' products. In this situation, firms investing in new plants and equipment face a high degree of risk, which reduces both the demand for capital stock and output growth. Therefore, policymakers in these countries should focus on stabilizing output growth and mitigating its negative effects on the economy. Furthermore, there is evidence that output growth uncertainty stimulates economic growth in the USA, Chile, and Jordan in their low-growth regimes. In their study, Neanidis and Savva (2013) have found that the effect of output growth uncertainty appears to be positive in the low-growth regime. In our study, we also observed a similar result for the USA. The positive impact of real uncertainty on growth in the low-growth regime, is in line with Schumpeter's theory of "creative destruction" (1939). According to this argument, the volatility of output growth is associated with recessions. During periods of economic contraction, firms are likely to spend more on research and development to develop more productive inputs, thereby boosting growth. Although uncertainty is beneficial to these three countries, a prolonged periods of uncertainty can adversely affect economic growth by fostering instability and a lack of confidence among investors. Policymakers must therefore carefully weigh the advantages and disadvantages of uncertainty when making decisions affecting economic growth.

In addition to the 'in-mean' effects, we are also interested in the associations between output growth and inflation. For this purpose, we employ the threshold Granger causality test (hereafter TGC) of Li (2006) to evaluate the predictive performance of a variable in the two regimes. The null hypothesis $H_0 : \psi_{i,12}^{l} = \psi_{i,12}^{h} = 0$ for all $i = 1, 2, \ldots, p$ implies that output growth has no effect on inflation in the two inflation regimes. Similarly, the hypothesis $H_0 : \psi^l_{i,21} = \psi^h_{i,21} = 0$ for all $i = 1, 2, \ldots, p$ indicates no threshold effect of inflation on output growth. In addition, we have conducted 'complementary tests' (Li 2006) to assess the regime-wise predictive power of the regressor. For instance, $H_0 : \psi^l_{1,12} = \psi^l_{2,12} = \ldots = \psi^l_{p,12} = 0$ indicates the impact of output growth on inflation in a low inflation regime. We first consider the TGC test, and if the test is found to be significant, only then the regime-wise 'complementary tests' are reported. The results indicate that in five countries, viz., Ireland, Spain, Barbados, Jordan, and South Africa, output growth has a significant impact on inflation, particularly in their high inflation regimes. Noticeably, the sum of the lagged coefficients of output growth affecting inflation $\left(\text{i.e.}, \sum_{i=1}^{p} \psi^h_{i,12}\right)$ is found to be positive for all the above countries. In Ireland and Jordan, regardless of the inflation regime, growth has a positive effect on inflation. This finding suggests that policies aimed at boosting economic growth in these countries may have unintended consequences on inflation, particularly in times of high inflation. It is important for policymakers to carefully consider the trade-offs between promoting economic growth and maintaining price stability. Furthermore, our findings show that the threshold effects of inflation on output growth exist in eight countries, viz., Malaysia, Portugal, Sweden, the USA, the UK, Barbados, Chile, and Jordan. This effect is significant at least in one output growth regime of these countries. However, we obtain mixed evidence regarding the signs of the effect (as measured by $\sum_{i=1}^{p} \psi^l_{i,21}$ and/or $\sum_{i=1}^{p} \psi^h_{i,21}$). In countries like Malaysia, the UK, Barbados, and Chile, inflation has harmful effects on growth only during periods of high output growth. In Chile, inflation has a negative impact in both regimes, but its magnitude is greater in high growth regimes. On the other hand, inflation boosts output growth in the USA and Sweden in the low growth regime and Jordan in both the regimes, with a larger magnitude in the low regime. According to recent studies, the impact of inflation on output growth is nonlinear and depends on the threshold level of inflation (Fischer 1993; Bruno and Easterly 1998; Ghosh and Phillips 1998; Khan and Senhadji 2001). The analysis in our paper differs from the existing studies, as we examine the causal effect in two output growth regimes instead of inflation regimes. Our findings contribute to the existing literature by suggesting that inflation has a nonlinear effect on economic growth and that is influenced by output growth regimes.

We will now discuss a few outcomes associated with the volatility models. In Panel B of the Tables 3 and 4, we present the test statistics for the null hypotheses of 'no-GARCH,' 'diagonal GARCH,' and 'no asymmetric GARCH' for all 19 countries. Based on the test results, the following conclusions can be drawn: first, the 'no GARCH' hypothesis was rejected for all 19 countries, indicating the presence of multivariate GARCH in the model innovations for these countries. Second, barring a few countries, the GARCH model is found to be non-diagonal. In addition, the coefficients of volatility model reveal that the spillover effect is bi-directional in Brazil, Malaysia, Austria, Greece, Sweden, Barbados, and Jordan, implying that nominal and real uncertainty influence each other in these countries. On the other hand, real uncertainty has a unidirectional effect on inflation uncertainty in countries such as Norway, Portugal, Spain, the USA, and South Africa, while the reverse causality holds for the

UK. Finally, our results suggest that the variance–covariance process is asymmetric in 13 countries. In each of these countries, the overall coefficient matrix, D [cf. Eq. (3)] is significant at a significance level of at least 10%, supporting that positive and negative innovations have different effects on the conditional variances of output growth and inflation. The coefficients d_{11} and d_{22} represent the effects of negative shocks in inflation and output growth on their respective volatilities. It is important to note that the coefficient d_{11} is insignificant in almost all countries. This finding is consistent with the empirical findings of Ungar and Zilberfarb (1993), Kontonikas (2004) who obtained that a low and less volatile level of inflation has a very little or negligible impact on inflation uncertainty. During the common policy periods, most of the countries in our sample exhibit low variability in the inflation rates. Therefore, it is expected that negative inflation shocks will have no effect on inflation volatility during these periods. Thus our findings indicate that the Friedman (1977) hypothesis does not hold true during low volatile periods of inflation. On the other hand, we found that real uncertainty is vulnerable to negative shocks in output growth in both developed and developing countries. In 11 countries, viz., Brazil, the Philippines, Norway, Malaysia, Austria, Portugal, Spain, Sweden, Barbados, Chile, and Jordan, the positive estimates of d_{22} indicate that 'bad news' of output growth affects output growth volatility more than 'good news' of equal magnitude. According to Easterly et al. (2000), the financial sector plays a crucial role in determining the volatility of output growth. Countries with weak financial sectors are burdened with a limited credit flow and ineffective equity management, which, in turn, forces firms to restrict their investment and production decisions. A weak financial sector in the presence of negative shocks not only increases the volatility of output growth, but also aggravates the economic downturn. A developed financial system, on the other hand, reduces the volatility of economic growth by smoothing out production opportunities. However, Easterly et al. (2000) have noted that, depending on the size of shocks, even a deeper financial system can also increase volatility. A more complex financial system can increase the risk of contagion and systemic crises, as interconnectedness among financial institutions can amplify the impact of shocks, thereby increasing output volatility. Therefore, both developing nations with a less developed financial sector and developed countries with a deeper financial system are susceptible to adverse output growth shocks.[13]

5 Conclusions

We have used bivariate 'in-mean' models to analyze the relationships between inflation, output growth and their respective uncertainties for 19 countries. The sample periods selected for this study reflect the era in which these countries adopted price stabilization policies. Our objective is to examine how country-specific heterogeneity, assumed to be reflected by average inflation and output growth rates, influences the relationships. In addition, our study draws conclusions regarding the volatility

[13] We have performed the Ljung-Box test on both standardized and squared standardized residuals to examine the adequacy of our models. However, we do not report them for brevity, but they are available on request.

spillover effect and the asymmetric effects of past output growth and inflation shocks on their uncertainties.

Our analysis indicates that country-specific heterogeneity plays a significant role in defining nonlinear relationships between macroeconomic uncertainties and performance. Additionally, we find that macroeconomic uncertainties have a greater impact on output growth than they have on inflation. The majority of the developed countries in our sample exhibit no relationship between inflation and inflation uncertainty, which favours effective price stabilization policies in these countries. On the other hand, developing nations are most affected by inflation uncertainty. Notably, the emerging economies that target inflation show a positive interaction between nominal uncertainty and inflation. This finding raises the possibility that inflation targeting policies in these nations may not be as successful as they are in other developed nations. This emphasizes the significance of policies that address both inflation targets and inflation uncertainty simultaneously. Policymakers should also make sure that their strategies for targeting inflation are credible and successful in achieving their objectives. In general, to ensure that their price stabilization policies are accomplishing their intended goals, central banks around the world must continue to track and assess them. Regarding the regime-dependent effects of nominal and real uncertainties on output growth, we observe that at least half of the thirteen countries exhibit significant relationships in each of these cases. It's interesting to note that both nominal and real uncertainty have significant effects on output growth, particularly during economic contractions. In general, uncertainties have a detrimental effect on output growth. To mitigate the negative effects of uncertainty on economic growth, policymakers may need to implement measures that promote economic stability and reduce its volatility. This may involve implementing policies that encourage business confidence and investment, providing fiscal stimulus during periods of economic contraction, and enhancing infrastructure and education in order to boost productivity and competitiveness. Ultimately, reducing uncertainty is crucial for sustaining long-term economic growth.

We find that output growth has a regime-dependent effect on inflation in countries like Ireland, Spain, Barbados, Jordan, and South Africa. Notably, in all these countries, output growth boosts inflation only in their respective high-inflation regimes. Further, inflation has a mixed effect on output growth in Malaysia, Portugal, Sweden, the USA, the UK, Barbados, Chile, and Jordan.

Moreover, our study reveals a significant spillover effect between nominal and real uncertainty across most of the countries in our sample. In a few countries, the spillover is unidirectional, and in the remaining countries, it is bi-directional. Finally, we find evidence that past shocks to output growth have had asymmetric effects on its uncertainty. In particular, we find that negative output growth shocks have a greater impact on uncertainty than positive shocks. The impact of these shocks can be harmful as they increase volatility, which inhibits output growth. Policymakers, therefore, must implement measures that promote financial stability and reduce systemic risk in order to mitigate the effects of these shocks. This includes strengthening regulatory frameworks, improving transparency and accountability in financial institutions, and promoting diversification in the financial sector. Additionally, countries should invest in building resilient economies that are less dependent on external factors and more capable of withstanding shocks. This can be achieved through policies that encourage innovation, entrepreneurship, and investment in human capital.

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Declarations

Conflict of interest The author has no relevant financial or nonfinancial interests to disclose.

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