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# A Counterfactual Analysis of the Effects of Climate Change on the Natural Interest Rate

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## Abstract

Climate change will potentially bring about important macroeconomic effects for all countries in the world and especially for emerging economies. I perform a counterfactual analysis to estimate the potential effect of global warming on the natural interest rate using a state-space semi-structural model of inflation and output determination. The model is estimated with quarterly data for Colombia for the period 1994-2019. I simulate gradual warming of 1°C during this period and include its potential effect on GDP growth and inflation according to recent cross-country estimations in the literature. The estimation with counterfactual data shows that the counterfactual natural interest rate decreases more rapidly to reach near 0% at the end of the period. This result is induced by the persistently negative effects of higher temperatures on trend output growth.

**Keywords**: Natural Interest Rate, Climate Change, Monetary Policy, Kalman filter

**JEL: E43, E52, Q51**

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## 1. INTRODUCTION

The Natural Interest Rate (NIR) is the real interest rate that allows output to reach its natural rate along with constant inflation except for transitory shocks. Therefore, the NIR is very important for monetary policy since it is the reference to determine its stance. If the real policy rate is above (below) the NIR, the stance is considered to be contractive (expansive). However, since the NIR is non-observed, it should be estimated with macroeconomic or econometric models. Traditional macroeconomic models show that the NIR is driven by the trend growth rate of natural output and by households' intertemporal preferences. Additionally, central banks should continually estimate the NIR, follow its evolution and understand better its determinants. Therefore, economists have proposed several methodological approaches to estimate this latent variable[1].

In this research paper I focus on climate change and specifically, global warming, as a potential additional determinant of the NIR due to its persistent macroeconomic effects. It is clear from the latest scientific reports that climate change is real, it is already present in current weather events and it will bring fundamental changes to all aspects of weather under most scenarios (IPCC, 2021). In particular, the copious emissions of greenhouse gases during recent decades have increased the global surface temperatures to be about 1.1°C greater than preindustrial levels (observed before 1850). The most optimistic scenarios show that temperatures will keep increasing during the current century to at least 1.5°C above pre-industrial levels. However, scenarios in which only the pace of current policies is implemented would lead to temperature increases of at least 3.0°C (NGFS, 2021).

Recent literature has identified that temperatures that exceed their expected levels or norms have important economic implications. On the one hand, Kahn et al (2021) estimate that temperature increases above a historical norm have significant negative effects on economic growth which lead to reductions of GDP per capita of 7% by the end of this century under a "current policies" scenario[2]. These results are obtained through panel data estimations with information for 174 countries. In addition, Mukherjee and Ouattara (2021) calculate panel VAR effects of temperature shocks with data for 107 countries.

This topic is of great importance for central banks since several studies have identified that the economic risks associated to climate change are expected to have some monetary policy implications. See for example, Bernal and Ocampo (2021) and ECB (2021) for a literature review on this topic. The literature shows that while central banks with inflation targeting regimes should maintain inflation expectations near their respective targets, higher macroeconomic volatility due to climate phenomena will probably slow down the transmission of monetary policy and the effects of central-bank communication. These risks will also imply financial stability effects that would require improved regulations and liquidity provision policies.

In this paper, I perform counterfactual empirical exercises to estimate the potential effect of climate change on the NIR. I study the macroeconomic effects of gradual warming and their implications for the NIR using Kalman filter estimations with actual and counterfactual data.

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[1] See Laubach and Williams (2003) for a well-known methodological approach to NIR estimation. Brand et al (2018) make a survey of alternative theoretical and empirical methodologies for this purpose.

[2] This is the effect on World's GDP per capita using a counterfactual analysis.

These counterfactual exercises use quarterly data for Colombia for the period 1994-2019 and consist of including the implications of a 1°C gradual temperature warming on economic growth and inflation and then estimating the NIR using this counterfactual information. The inflationary implications of climate change are initially assumed to be neutralized by the lower rate of economic growth and Central Bank credibility. Then this assumption is relaxed to include full inflationary pressures along with a mild monetary policy reaction.

The results of these counterfactual exercises show gradual reductions of the counterfactual NIR with respect to the NIR estimated with actual data. While the latter is estimated to be 2.1% at the end of 2019, the former is estimated to be close to 0%. This effect on the NIR is driven by the lower GDP trend growth which gets reduced from average quarterly growth rates of about 0.6% to slightly negative rates in the counterfactual scenarios. This result is robust to the presence of inflationary pressures as long as the monetary policy reaction keeps the real interest rate at their historic levels.

This counterfactual analysis is a thought experiment that allows us focusing on the productivity-growth transmission channel from climate risks to the NIR and the potential effects under a rapid global warming scenario. Since the analysis is performed within the sample period, it does not include most of the debates around the projections of GDP growth, population, inflation, monetary policy strategies and technological innovations. The whole inclusion of alternative forecasts assumptions, climate scenarios and transmission channels, would amplify the number of possible future paths of the NIR to extents that can be difficult to comprehend.

This study contributes to the literature on the monetary policy implications of climate-change by analyzing the productivity-growth channel within one of the most widely used frameworks for the determination of the NIR. This is the state-space semi-structural framework proposed by Laubach and Williams (2003) and further developed by Holston et al (2017) among others. In addition, this study includes robustly estimated macroeconomic implications of global warming on both GDP growth and inflation according to recently published articles. Recent related papers such as Cantelmo (2020) and Dietrich et al (2021) employ the disaster-risk asset pricing framework which mostly captures the risk-aversion transmission channel of climate change (ECB, 2021). This paper focuses instead on the productivity growth transmission channel.

This paper is organized in the following way. After this introduction, Section 2 describes a brief review of related literature. Section 3 presents the state-space model and the counterfactual exercise. Section 4 describes the data. Section 5 shows the empirical results along with robustness checks. Finally, the last section makes some concluding comments.

## 2. RELATED LITERATURE

Overall, this paper lies at the crossroads of the literature on the determinants and estimation of the natural interest rate (NIR) and the literature on the macroeconomic effects of climate change. Recent research documents have focused on qualitatively describing the alternative channels of transmission from climate change to the NIR. A few recent quantitative papers analyze the risk-aversion channel of transmission. However, additional studies examining alternative channels are still needed.

Laubach and Williams (2003) perform a well-known estimation of the NIR for the United States using a state-space model. This model is based on the theoretical definition of the NIR as the steady-state equilibrium real interest rate which is a function of long-term productivity growth and of parameters related to intertemporal utility and risk aversion. This model also acknowledges that the NIR should be consistent with cyclical fluctuations of GDP and inflation by including an aggregate demand curve and a Phillips curve, respectively.

Messonier and Renne (2007) estimate the NIR for the Eurozone using the methodology by Laubach and Williams (2003) but including a few specification improvements which allow better identifying the NIR and minimizing the uncertainty of the model's parameters. Several of these improvements are included in the current estimation. Holston et al (2017) describe updates of the NIR estimation for the US, following Laubach and Williams (2003), and also new estimations for the Euro Zone, Canada and the United Kingdom in which several enhancements on the initial estimation conditions are incorporated.

Recent literature has applied new ideas for the estimation of the NIR. Some of them are further modifications of the semi-structural framework of Laubach and Williams (2003). Other approaches use DSGE models to perform estimations in general equilibrium with further micro-foundations about the economic transmission channels. A survey and discussion about these recent approaches is presented by Brand et al (2018).

Table 1 – Transmission Channels of Climate Change

| Transmission Channel | Details | Effect on NIR |
|---|---|---|
| Demographic trends | Warming leads to lower labor supply but also to possible rebalancing of age composition. | Ambiguous |
| Productivity Growth | Higher physical and transition risks reduce productivity growth, but new technology can compensate this reduction in the long run. | Negative |
| Risk Aversion | Higher risk premia due to increased uncertainty about climate relate risks, leads to augmented demand for safe assets. | Negative |
| Fiscal Policy | Higher mitigation and adaptation expenditures can increase public debt in most countries. | Positive |
| Income Inequality | Potential intensification of income inequality reduces consumption and increases desired savings | Negative |

Source: ECB (2021, chapter 5)

A few policy papers qualitatively describe the possible effects of climate change on the NIR. For example, NGFS (2020) and ECB (2021) describe several possible transmission channels and regard the net effect as ambiguous because of the presence of positive as well as negative potential effects. Table 1 briefly describes most of these transmission channels. These documents also acknowledge that the productivity growth channel is likely the strongest one.

Other papers compute quantitative effects. Cantelmo (2020) incorporates disaster risk within a New Keynesian model to study the effect of increasing risk (due to climate change, among others) on the NIR. The results show that the net effect depends on the relative strength of demand versus supply-side effects from disasters. If there are strong negative effects on capital and asset prices, then the effect can be positive due to a higher profitability of new investments.

Muller (2021) computes a green interest rate as an alternative to the NIR that takes into account the environmental damage effect on GDP. This green interest rate is higher than the traditional NIR, especially in periods when economic activity is thriving and therefore environmental damage is more perceptible. However, it is unclear how central banks would include this green interest rate into their monetary policy frameworks.

Dietrich et al (2021) use information from a survey to US households about the expected frequency and economic effect of future natural disasters, to calibrate a New-Keynesian model incorporating low-probability disaster risk. The resulting NIR is 65 basis points lower than the NIR computed from a similar model with no disaster risk. The main transmission channel analyzed by Cantelmo (2020) and Dietrich et al (2021) is the effect of climate change on the perception of economic and financial risks by households and investors.

My paper contributes to the literature by performing a counterfactual experiment about the potential effects of climate change on the NIR which consists of simulating a gradual and persistent warming of 1°C and including its effects on economic growth and inflation within a state-space semi-structural model for the NIR estimation and with macroeconomic data for Colombia. This exercise allows focusing on the productivity growth channel of transmission. This experiment includes the macroeconomic effects from climate change as robustly estimated in recently published articles using panel data for several economies. These details are described below in Sections 3 and 4.

## 3. ECONOMETRIC METHODOLOGY

The estimation is based on the approach by Laubach and Williams (2003) and Messonier and Renne (2007) consisting of a state-space model with two main measurement equations: inflation (Phillips Curve) and GDP gap (aggregate demand). The natural interest rate (NIR) is measured as a latent variable which should be consistent with the evolution of the GDP gap, inflation and nominal interest rates. In addition, I include temperature anomalies as controls on both measurement equations to better capture the transmission channels. Therefore, latent variables should also be consistent with the effect of temperature anomalies on both GDP and inflation.

The state-space model has the following measurement equations:

$$\tilde{y}_t = a_y \tilde{y}_{t-1} + a_r (r_{t-1} - r^*{}_{t-1}) + a_T \hat{T}_{t-1} + \varepsilon_{1,t} \quad (1)$$

$$\pi_t = b_\pi \pi_{t-1} + b_y \tilde{y}_{t-1} + b_T \hat{T}_{t-1} + \varepsilon_{2,t} \quad (2)$$

$$r^*{}_t = \mu_r + c g_t \quad (3)$$

$$\tilde{y}_t = y_t - y^*{}_t \quad (4)$$

It also includes the following transition equations:

$$y^*{}_t = y^*{}_{t-1} + g_{t-1} + \varepsilon_{3,t} \quad (5)$$

$$g_t = \varphi g_{t-1} + \varepsilon_{4,t} \tag{6}$$

Equation 1 represents the evolution of the output gap $\tilde{y}_t$ as function of its own lag, the difference of the real policy rate r from the NIR (r*) and anomalies of terrestrial temperatures $\hat{T}_t$. Temperature anomalies are defined as positive differences of observed temperatures with respect to temperature norms. The latter are defined as moving averages of the observed temperature series during the previous 20 years. These anomalies are assumed to affect economic activity one quarter ahead.

Equation 2 represents a Phillips curve in which total inflation is a function of its own lag, the lagged output gap and temperature anomalies. Equation 3 defines the NIR as a linear function of trend growth (g) and intercept. Equation 4 defines the output gap as the log difference between observed output and its potential level ${y^*}_t$. Equation 5 specifies that potential output accumulates itself and evolves with trend growth and independent shocks. Finally, Equation 6 defines trend growth as an autoregressive process with stochastic shocks. I assume that $\varepsilon_{1,t}$, $\varepsilon_{2,t}$, $\varepsilon_{3,t}$ and $\varepsilon_{4,t}$ are serially and contemporaneously uncorrelated innovations.

Equations 1 to 6 are estimated using a Kalman filter and historic macroeconomic data for Colombia. The output from this estimation are time series for the natural output level (${y^*}_t$), trend growth ($g_t$) and the NIR (${r^*}_t$) as well as estimated structural coefficients.

Why using this particular approach and specification? This linear approach to estimate the NIR using a state-space model with equations for aggregate demand and the Phillips curve was proposed by Laubach and Williams (2003) and since then it has become a widely used methodology. However, the specification in Equations 1 to 6 is closer to the simplified and refined model presented by Mesonnier and Renne (2007). In particular, I follow their approach by specifying the NIR as an autoregressive process and by computing the real interest rate with expected inflation indicators as taken from surveys to economic analysts[3].

The Kalman filter requires initial values for all unobserved variables and parameters to estimate Equations 1 to 6. These initial values are calculated using a Hodrick-Prescott Filter applied to the observed real interest rate and GDP. These initial estimations for unobserved variables as well as the remaining observed variables are employed to estimate equations 1, 2 and 6 using least squares regressions in order to obtain initial values for the coefficients of the model.

The Kalman filter estimation requires a few assumptions which are useful to simplify and better identify the state-space model originally suggested by Laubach and Williams (2003). In addition, these simplifications are needed for a more efficient NIR estimation according to recent literature. In this sense, Mesonnier and Renne (2007) propose simplifying the specification of the model, Echavarria-Soto et al (2007) propose calibrating the parameters of the NIR equation and Buncic (2020) shows the existence of econometric problems behind the three-stage procedure to estimate the variance ratios for innovations as originally proposed by Laubach and Williams (2003).

Following this literature, our Kalman filter estimation requires a few assumptions about parameters which have been deemed difficult to empirically identify. For example, while there

[3] In this paper, inflation expectations are only used for the computation of the real interest rate.

are four innovations in Equations 1, 2, 5 and 6, it is difficult to identify the variance of shocks to latent variables such as $\varepsilon_{3,t}$ in the potential output equation. To fix this identification issue, the variance of $\varepsilon_{3,t}$ is assumed to be proportional to the variance of $\varepsilon_{1,t}$, and the variance ratio is computed using initial estimations. On the other hand, since both the NIR and trend growth (g) are latent variables, it is difficult to properly identify the parameters of Equation 3, and therefore, they must be calibrated. The risk aversion parameter (c=2) is taken from standard asset-pricing models. Additionally, the intercept ($\mu_r$) is calibrated so that the initial NIR be similar to the observed real interest rate.

The first counterfactual exercise consists of estimating the state space model of equations 1-6 with artificial data for temperature anomalies ($\hat{T}_t$) and GDP ($y_t$) and including additional assumptions on the counterfactual behavior of both inflation and the real interest rate. I simulate gradual warming of 1°C during the 25-year period of estimation, which corresponds to 0.01°C each quarter. This warming is added to the observed temperature anomalies in Colombia during the same period. The gradual effects of such increasing temperatures on GDP are computed using the results obtained by Khan et al (2021) with panel data about the effect of temperature anomalies on GDP growth for 174 countries. On the other hand, several studies in the literature show a positive effect of temperature anomalies on consumer inflation. For example, Mukherjee and Ouattara (2021) show a positive and significant effect of temperature shocks on consumer inflation with panel VAR information for 107 economies[4].

In the first experiment, these upward inflationary pressures are assumed to be fully neutralized by the negative effects of temperature anomalies on economic activity. Additionally, monetary policy is assumed to stay acyclical due to the simultaneous presence of inflationary pressures and lower economic growth. While total inflation is assumed to stay unchanged, a composition change is expected in which food and utilities reflect supply side inflationary pressures and core inflation remains low due to weak aggregate demand.

In the second experiment, upward inflationary pressures are assumed to manifest themselves according to the panel data estimations of Mukherjee and Ouattara (2021) for developing economies. In this case, monetary policy is assumed to tighten in such a way that, despite the higher observed and expected inflation, the real interest rate remains unchanged. The effect of temperature anomalies on economic activity is the same in both experiments.

## 4. DATA DESCRIPTION

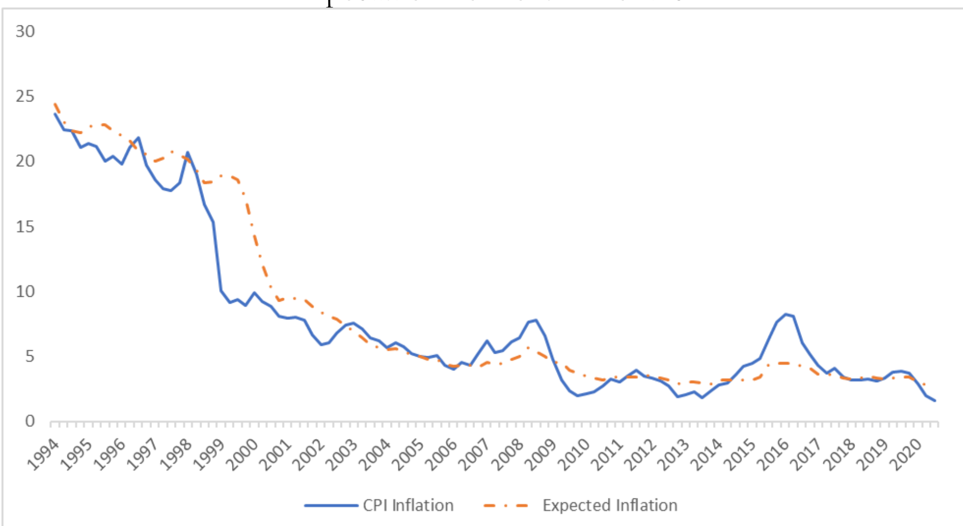
I use quarterly GDP data which is seasonally adjusted information collected from the Colombian Department of Statistics (DANE). I also use the Colombian interbank interest rate which is the rate for overnight loans among commercial banks and which closely follows the Central Bank's nominal monetary policy rate. I compute the real interest rate by deflating this nominal rate with the expected consumer inflation rate, one year ahead, as measured by surveys to professional

[4] The reason for using macroeconomic sensitivities to gradual warming estimated in panel studies for several countries, is that these estimations are robust to the presence of many other concurrent shocks to economic activity and inflation. Therefore, these estimations incorporate a more precise identification of temperature shocks and a more efficient use of information which is available for most countries in the world.

forecasters. Observed consumer inflation rates are also retrieved from DANE's webpage[5]. Figure 1 shows observed versus expected inflation. Figure 2 shows nominal versus real policy interest rates.

Inflation expectations correspond to the average of analysts' expectations according to the Central Bank's monthly survey of economic expectations. Data from this survey are available only starting on July 2003. Therefore, expectations from 1994Q1 to 2003Q2 are econometrically estimated using 12-month ahead forecasts from autoregressive models. These inflation expectations are only used for the computation of the actual real interest rate.

Figure 1: Observed and Expected Consumer Inflation in Colombia
Expectation horizon:12 months

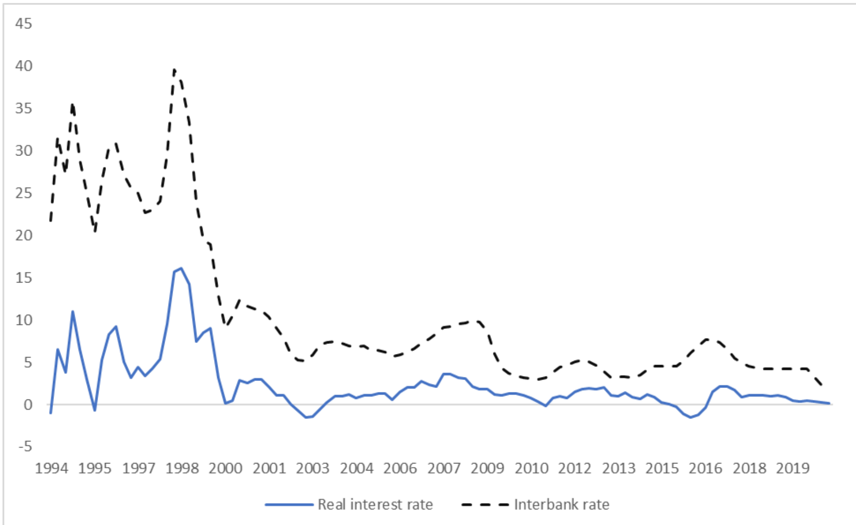



Source: Colombian Department of Statistics, Central Bank of Colombia (Banco de la Republica) and own computations.

I use quarterly terrestrial temperature data from the World Bank's Climate Knowledge Portal. These data correspond to averages across regions for Colombia for the period 1960-2020. Following Khan et al (2021), the most relevant climate indicator to study economic performance is temperature anomalies. These anomalies are computed as the positive temperature innovations with respect to a trend or norm, which is calculated using 20-year moving averages. The goal of these computations is incorporating a degree of economic adaptation to gradual changes in temperature. Therefore, only temperature surprises with respect to a 20-year-old norm are assumed to have economic effects.

5 https://www.dane.gov.co/index.php/en/

Figure 2: Nominal versus real policy interest rates in Colombia
Percentage points



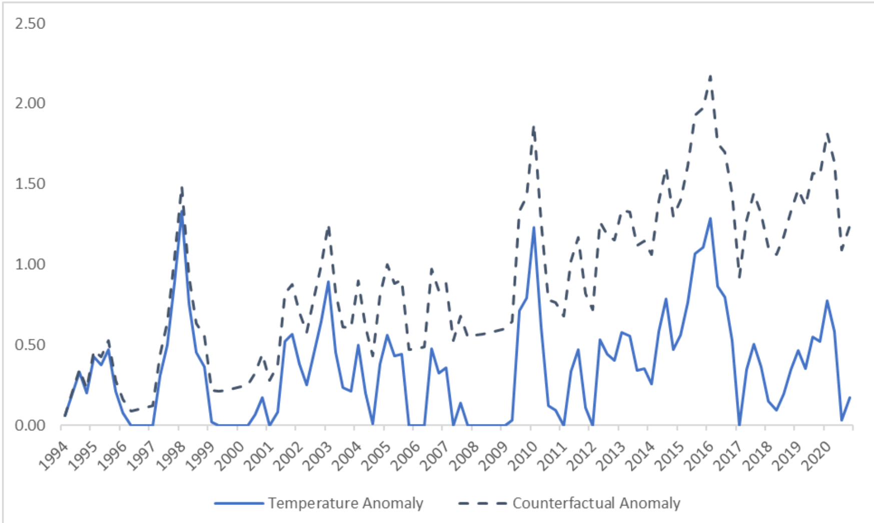

Source: Colombian financial supervisor, Central Bank of Colombia (Banco de la Republica) and own computations.

In the counterfactual exercise, I simulate a gradual warming of 1°C during the 25-year period 1994-2019. Therefore, it corresponds to gradual increases of 0.01°C during 100 quarters. Notice that these simulated warming data are added to the actual data on temperature anomalies. If we include the implicit temperature trend, the total warming at the end of the sample is approximately 1.4°C[6]. It is also important to highlight that such warming speed during a quarter of a century, corresponds to a pessimistic business-as-usual (BAU) scenario. This setting has been studied as the representative concentration pathway (RCP) 8.5 in research articles such as Burke et al (2015) and Hsiang et al (2017) and corresponds to scenarios with additional warming of 3°C throughout the current century. Figure 3 shows the historical temperature anomalies for Colombia and the counterfactual simulation.

Khan et al (2021) use panel data for 174 countries and temperature anomalies to compute the effect of these anomalies on GDP growth. Their panel data estimation allows to control for the effect of other shocks on economic growth. Their main results show that a 0.01°C temperature increase leads to lower annual economic growth of 0.0543% during the following year. I incorporate this effect in the actual GDP data by quarterly simulating the effects of gradual warming on the observed GDP growth series for Colombia. Figure 4 shows both the actual and the counterfactual GDP growth data.

[6] Therefore, the trend warming during this 25-year period (1994-2019) in Colombia is approximately 0.4°C.

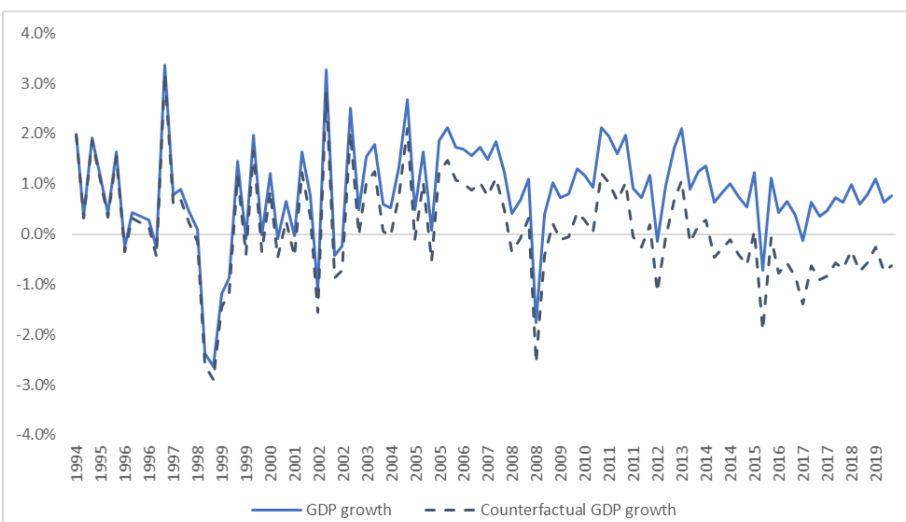
Figure 3: Temperature anomalies in Colombia and 1°C gradual warming




Source: World Banks's Climate Knowledge Portal and own computations.

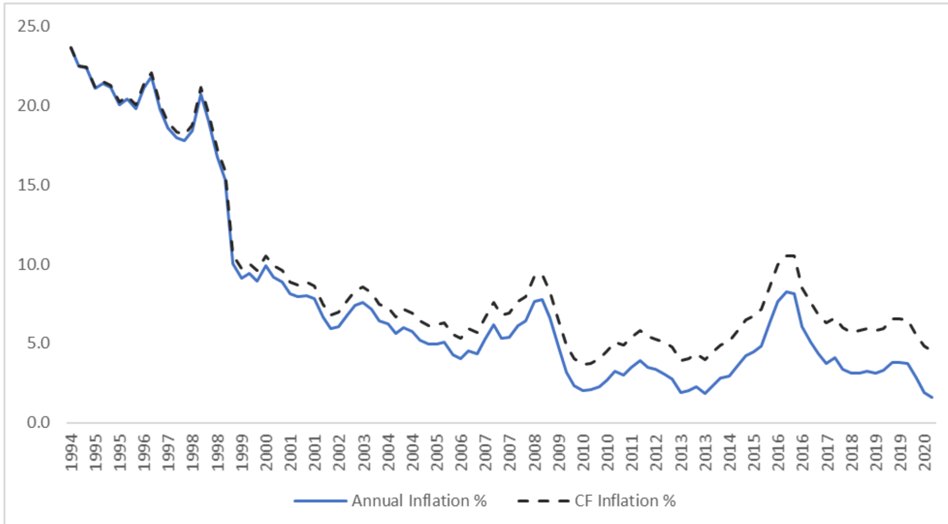
I also incorporate the effects of climate change on inflation according to several estimations about this effect in the literature. A very recent estimation is described by Mukherjee and Ouattara (2021) in which a panel VAR is used to estimate the effects of temperature shocks on inflation with data for 107 countries. These authors find that a 1% warming shock leads to higher inflation of 2.6% during the first year after the shock in the case of developing economies. This result is robust to other shocks on inflation across countries due to the structure of the panel estimation. I include this effect on the total inflation series of Colombia by adding the effect of the gradual warming as a quarterly additional temperature shock that increases inflation one quarter ahead. Figure 5 shows both the actual and the counterfactual inflation data.

Figure 4: Quarterly GDP Growth: Actual and counterfactual data




Source: Colombian Department of Statistics and own computations.

Figure 5: Inflation: Actual and counterfactual data




Source: Colombian Department of Statistics and own computations.

## 5. EMPIRICAL RESULTS

In this section, I describe Kalman Filter estimations using actual and counterfactual data, respectively. The results from these estimations are then compared with each other to analyze the potential effects of climate change not only on potential output but also on the natural interest rate. I present two counterfactual experiments to check how sensible the results are to alternative assumptions.

Table 1: Results from Kalman Filter Estimation with Actual Data

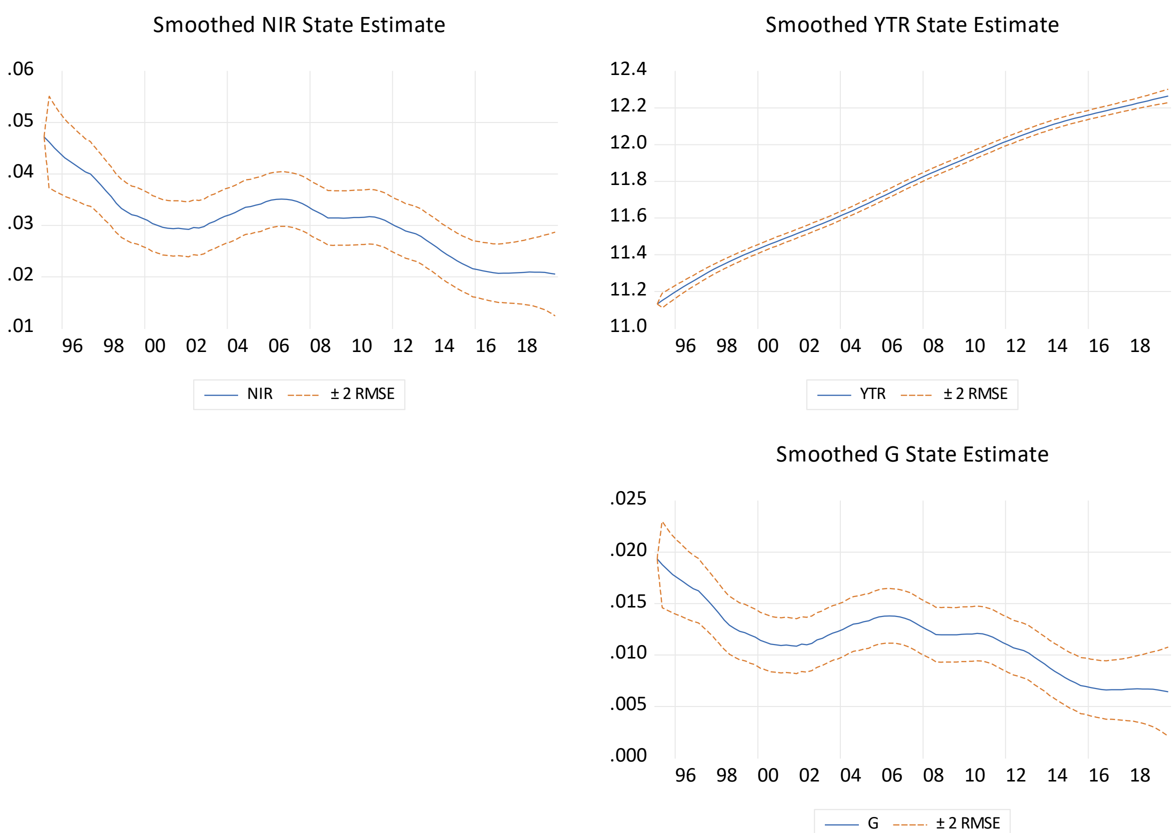
| Coefficient | Estimated value | P-value |
|---|---|---|
| $a_y$ | 0.9701 | 0.0000 |
| $a_r$ | -0.1239 | 0.0000 |
| $a_T$ | -0.0012 | 0.7400 |
| $b_\pi$ | 0.7849 | 0.0000 |
| $b_y$ | 0.1147 | 0.0064 |
| $b_T$ | 0.0057 | 0.0166 |
| $\varphi$ | 0.9854 | 0.0000 |

Source: Own computations.

Table 1 shows the estimated coefficients of the model presented in Section 3 using actual data for Colombia as described in Section 4. The first set of coefficients consists of persistence measures for each variable: output gap ($a_y$), inflation ($b_\pi$ ) and trend output growth ($\varphi$). Trend output growth is found to be the most persistent variable due to the slow movement that this variable implies (Figure 6). The second set of coefficients shows the slopes of both the aggregate demand ($a_r$) and Phillips-curve ($b_y$) equations. Both coefficients have the expected signs which are crucial for the adjustment of the model through the effect of monetary policy on the output gap and therefore on inflation. The third set of coefficients consists of the effects of temperature anomalies on both the output gap ($a_T$) and inflation ($b_T$). Both estimated coefficients have the expected signs since the empirical literature has found that such anomalies lead to reduced economic activity and inflationary pressures. Additionally, both estimated coefficients lead to economically significant effects of temperature anomalies. However, the coefficient $a_T$ is not statistically significant due to the inherent uncertainty of the joint estimation of the semi-structural model[7].

The Kalman Filter procedure also produces estimations and confidence intervals for the latent variables. There are two main ways to compute the estimated levels of these latent variables. First, filtered or one-sided computations only use current and past data which makes it closer to a real-time estimation. Second, two-sided or smooth computations use the whole sample period for the calculations. Following Laubach and Williams (2003), I focus on the smoothed results of the latent variables since the goal of the exercise is doing a comparison, for the whole period, of the alternative experiments.

Figure 6: Latent variables from the estimation with actual data




Source: Own computations.

[7] Other estimations such as Mesonnier and Rennes (2007) and Buncic (2020), also report non-significant coefficients associated to controls on inflation and output gap. The coefficient $a_T$ implies a significant effect on output since 1°C of additional temperature leads to 12 basis points of lower GDP gap.

Figure 6 shows the results for the latent or state variables with observed data including confidence intervals with a range of two standard deviations. The first graph shows the estimated evolution of the NIR (r*) from 1996 to 2019. This interest rate has a decreasing trend since 2006 in line with results in the literature for several economies. The highest NIR (4.7%) took place at the beginning of the sample, then it fluctuates between 3% and 4% until 2012 and after that it went down gradually ending the estimation period on 2.1%. The second graph shows the estimated potential output (${y^*}_t$) capturing GDP's long-run trend. The third graph shows the estimation of the output's trend growth ($g_t$) which is expressed in quarterly growth rates. This variable, according to Equation 5, roughly corresponds to potential output's growth rate but subject to its own short run innovations. Notice also that the first and third graphs show some similarity since the NIR is an affine function of output's trend growth according to Equation 3.

Table 2 presents the results of the estimated coefficients for the first counterfactual experiment. In this case, counterfactual data for GDP and temperature anomalies are included but inflationary pressures are assumed to be contained. These counterfactual data include a gradual warming of 1°C during the analysis period (1994-2019) and its effect on GDP growth according to panel-data estimations in the literature as described in Section 4. The resulting coefficients are overall similar to those presented in Table 1 with actual data. There are some changes on the persistence degrees but the significance levels of most coefficients remain similar to those obtained with actual data.

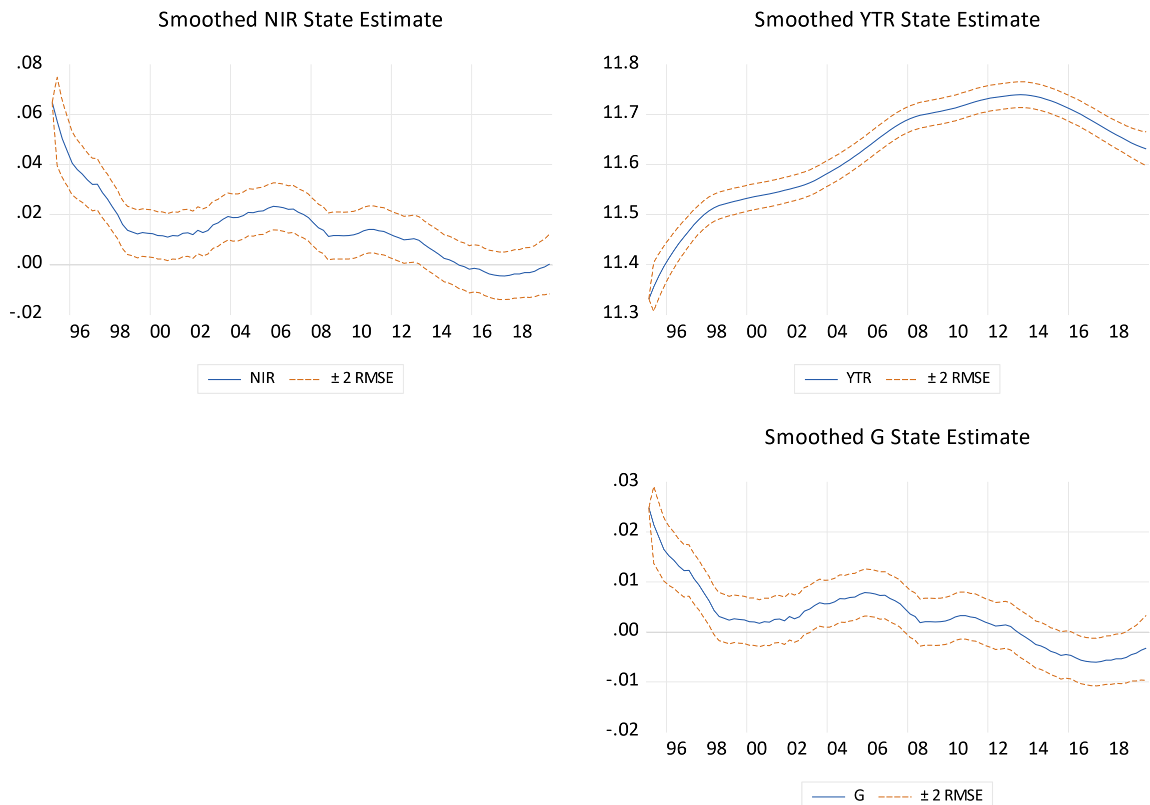
Table 2: Results from Kalman Filter Estimation of the First Counterfactual Experiment

| Coefficient | Estimated value | P-value |
|---|---|---|
| $a_y$ | 0.9178 | 0.0000 |
| $a_r$ | -0.1013 | 0.0060 |
| $a_T$ | -0.0011 | 0.7498 |
| $b_\pi$ | 0.8988 | 0.0000 |
| $b_y$ | 0.1146 | 0.0058 |
| $b_T$ | 0.0054 | 0.0358 |
| $\varphi$ | 0.8849 | 0.0000 |

Source: Own computations.

Figure 7 shows the latent variables from the first counterfactual experiment. The first graph shows the estimated evolution of the NIR on this counterfactual scenario. This variable shows a decreasing trend at the beginning of the period to reach 1.4% in 1999, then it increases gradually to reach 2.3% in 2006 and finally declines until 0.0% at the end of 2019. This result is due to the accumulated effect of the gradual and abnormal warming on GDP growth. The Kalman filter allocates a significant proportion of such effect to potential output and hence to trend GDP growth. The second graph shows that potential output stops increasing around 2013 and then bends over due to the persistently negative effects of warming on potential output. The third graph shows the corresponding implications on trend growth which becomes negative from 2013 to 2019.

Figure 7: Latent variables from the first counterfactual experiment




Source: Own computations.

The main result of the first counterfactual experiment is the comparison between counterfactual and actual NIRs. The resulting effect of a 1°C gradual warming is the reduction, through the productivity growth channel, of 210 basis points on the NIR at the end of the analysis period. This result corresponds to scenarios with rapid global warming and very scarce climate-change mitigation policies. In addition, this outcome is derived from the assumption of neutralized inflationary pressures due to low GDP growth. If inflation is not fully neutralized then the final result would depend on the monetary policy reaction. Under a very strong (hawkish) monetary policy reaction, for example, the counterfactual real interest rate should be higher than the actual rate and the final effect of climate should be lower than 210 bp. The opposite result is expected in the case of a dovish monetary policy reaction to these inflationary pressures.

On the other hand, it is clear that NGFS (2021) considers other climate scenarios in which global warming is lower and most countries in the World would implement climate mitigation policies including increasing carbon taxes. Such scenarios would lead to intense negative economic growth effects in the short-run due to the costs associated to mitigation policies. In addition, higher carbon taxes would conduct to significant inflationary pressures in the short-run. However, in the medium and long terms, technological innovations related to clean energies and carbon capture are expected to compensate for these economic costs leading to normalized scenarios of economic growth and inflation. Therefore, a negative effect on the NIR should be expected under those mitigation scenarios but this effect should last only a few years while most economies around the world bear the initial mitigation costs.

As a robustness check, I perform a second counterfactual experiment in which inflationary pressures are not contained. In this case, the counterfactual data include temperature anomalies, GDP and inflation. The counterfactual effect on inflation is calculated according to the estimations by Mukherjee and Ouattara (2021) as described in Figure 5. Monetary policy is assumed to react to inflation by increasing the nominal rate such that the real interest rate remains equivalent to its observed levels. This reaction is likely a middle point between a hawkish and a dovish monetary policy response. The counterfactual levels of GDP and temperature remain similar as in the first experiment.

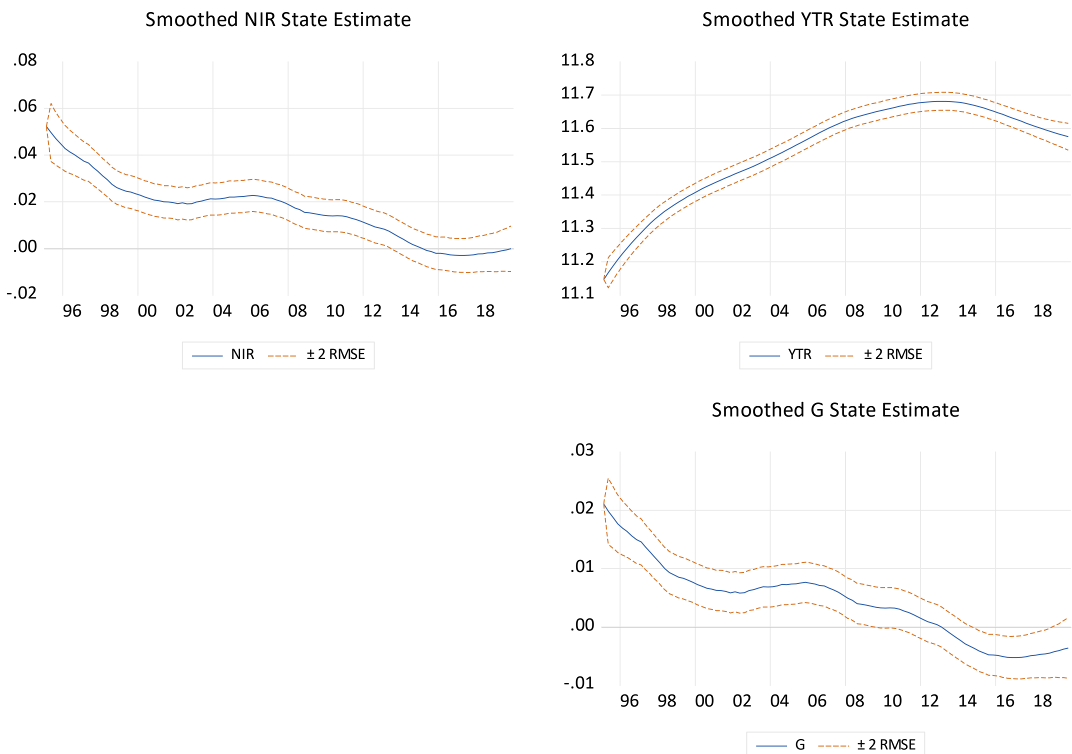
Table 3: Results from Kalman Filter Estimation of the Second Counterfactual Experiment

| Coefficient | Estimated value | P-value |
|---|---|---|
| $a_y$ | 0.9646 | 0.0000 |
| $a_r$ | -0.1065 | 0.0020 |
| $a_T$ | 0.0006 | 0.7948 |
| $b_\pi$ | 0.8043 | 0.0000 |
| $b_y$ | 0.1094 | 0.0225 |
| $b_T$ | 0.0063 | 0.0147 |
| $\varphi$ | 0.9528 | 0.0000 |

Source: Own computations.

Table 3 shows the estimated coefficients for the second counterfactual experiment. Overall, these coefficients are similar to those presented on the first experiment. Figure 8 shows the latent variables from the second experiment. The results are similar to those presented in Figure 7. The main difference of the resulting NIR is that it is smoother than in the first experiment. However, the estimated NIR at the end of the period (2019) is similar in both experiments and therefore the computed effect of gradual warming on the NIR remains similar as well. The reason for this finding is that inflation only indirectly affects the determination of the NIR. If monetary policy is more (less) hawkish than in the assumption made for the second experiment, then the resulting NIR would be higher (lower) showing the importance of this factor for the effects of climate change on the NIR.

Figure 8: Latent variables from the second counterfactual experiment




Source: Own computations.

## 6. CONCLUDING COMMENTS

This paper analyzes the potential effects of climate change on the Natural Interest Rate (NIR) using a counterfactual experiment. This experiment consists of simulating gradual warming of 1°C during a 25-year period, and computing its effects on GDP and inflation. This warming speed is consistent with business-as-usual scenarios in which the additional warming during the whole century is of at least 3°C. However, the counterfactual methodology allows focusing on the NIR determination model and the transmission mechanism without having to include all the possible assumptions and debates about future projected levels of output, inflation and interest rates.

This experiment uses a state-space semi-structural model based on Laubach and Williams (2003) but incorporating several econometric refinements suggested in the literature. This model considers mainly the productivity-growth transmission channel from climate change to the NIR and it is estimated with actual and counterfactual data for the period 1994Q1 to 2019Q4.

The counterfactual data consists of gradually increasing temperatures and their effects on economic activity according to panel-data and cross-country estimations presented by Khan et al (2021). Gradual warming also brings about inflationary pressures according to several estimations in the literature. However, on the first experiment it is assumed that the effects of these supply-side inflationary pressures on inflation are neutralized by the lower GDP growth rate and by Central Bank credibility within an inflation-targeting regime. In addition, it is assumed that monetary policy stays acyclical due to the simultaneous presence of inflationary pressures and lower output growth.

The results show a gradual reduction of the counterfactual NIR with respect to the NIR estimated with actual data. The main result is that by the end of 2019, the counterfactual NIR is very close to 0% versus an actual NIR of 2.1%. This result is driven by the reduction of trend output growth implied by global warming. Specifically, the Kalman filter starts attributing diminishing GDP growth to lower potential output levels from 2013 onwards. These findings however are caused by a significant warming speed which is only consistent with business-as-usual scenarios in the whole world. Almost any other scenario would produce lower and less rapid warming and therefore less persistent effects on the NIR. The second counterfactual experiment includes the counterfactual inflationary effects of gradual warming. In this case, the results remain similar to the first experiment as long as the monetary policy reaction to a higher inflation leaves the real interest rate unchanged.

These counterfactual exercises are thought experiments that allow focusing on the transmission mechanisms from climate change to the NIR without incorporating all the debates associated to the projected paths of GDP, inflation and the real interest rate. This semi-structural framework only analyzes the productivity-growth channel of transmission. However, other channels identified by the literature are either ambiguous or have a negative expected effect. The exception is the potentially positive effect from steep increases of public debt as a result of higher public expenditure on mitigation of and adaptation to physical climate risks. Therefore, models incorporating this fiscal channel would be required on future extensions.

According to ECB (2021), a negative effect on the NIR that takes it closer to its effective lower bound, would mainly imply a reduced space for conventionally expansive monetary policy and therefore further use of unconventional monetary policy tools would be required. Lower Central Bank credibility would increase the negative effects on the NIR. However, scenarios with climate mitigation policies would render the effect on the NIR to be less persistent.

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