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Abstract

Climate change, through temperature anomalies, is likely to have an asymmetric effect on prices and economic activity within the euro area. In this paper, we aim to measure the monetary stress for each member country resulting from these asymmetric shocks. For that purpose, we first measure how inflation and GDP per capita respond to temperature anomalies in several euro area countries. As a second step, we simulate the temperature-induced changes in inflation and GDP per capita over the period 2025-2100. The significant divergences in these temperature-induced variables call for different monetary policy needs within the currency union, hence the existence of a temperature-induced monetary stress that is likely to worsen over time. Our results provide evidence that climate change constitutes a challenge to the sustainability of the currency union and to the one size fits all ECB's policy.

Keywords: temperature anomalies, currency union, monetary stress, euro area.
JEL classification: E02, E58, Q54.

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1 Introduction

Central banks have been placed, *nolens volens*, at the forefront of the fight against climate change. There have been calls to include this objective as one of their explicit goals and arguments have been made for central banks to exclude some assets from their operations, to favor "greener" industries and activities (Liebich et al., 2023), and to act as leader, not follower, on the subject (Campiglio et al., 2018). As an illustration, the European Central Bank has a climate action plan following the conclusion of its review of monetary policy strategy published in 2021.

However, on a day-to-day basis, climate change also implies that central banks will face different types of demand and supply shocks with significant implications in terms of price stability (Chen et al., 2021). For instance, on the supply side, events such as droughts will likely increase food price volatility while on the demand side, hot weather may reduce household demand in the retail sector which may push the prices down. The prevalence of supply shocks over demand shocks (or the opposite) is paramount for the conduct of monetary policy. Indeed, while central banks can manage demand-side shocks given that there is no trade-off between stabilizing prices and output in this framework (Mankiw et al., 2005), they tend to struggle when confronted with supply-side shocks.

In monetary unions, the challenges faced by central banks will be even harder to tackle, as shocks induced by climate change may not strike the whole area similarly, creating both upward and/or downward pressures on prices within the currency union.[1] In this context, the central bank is likely to face asymmetric responses to temperature anomalies, which illustrate deviations with regard to the historic averages. This raises a crucial issue since a single monetary policy is, by definition, not designed for spatially differentiated shocks. Climate change will, however, give a new twist to the issue, as its macroeconomic consequences will not be spread out homogeneously within the monetary union, making it harder for a common central bank to address its asymmetric effects.

In this article, we consider this issue in the context of the euro area, and we analyze

[1]Extreme temperatures are found to be either inflationary (Kim et al., 2021; Makkonen et al., 2021) or deflationary (Faccia et al., 2021).

the consequences of climate change on the cost and standard of living for its member countries. More precisely, we consider the case of temperature anomalies that climate change will engender, and how they will affect the macroeconomic situation of the euro area member countries. Temperature anomalies allow us to take the case of one of the consequences of climate change that may be considered as the closest to a uniform change, compared to natural disasters for example. As a consequence, our results can be considered as a low-case scenario. Nevertheless, as we expose, even this low-case scenario is likely to increase significantly the stress of living in a monetary union, that is, the divergence between the required monetary policy rate for a member country to achieve its price stability objective and the policy rate required for other countries. In other words, as much as temperature anomalies have different effects on inflation and growth for euro area member countries, they modify the trade-off of the benefits of being in a currency union.

To measure the temperature-induced monetary stress in the euro area, We first assess how the European central bank's (ECB) macroeconomic objectives, price stability and economic growth, are affected by temperature anomalies in euro area countries using the method of local projections. Second, we use the coefficients estimated in the first step along with climate projections obtained from the sixth Intergovernmental Panel on Climate Change (IPCC) report to derive the temperature-induced changes in inflation and GDP per capita for the period 2025-2100. The climate-economy relationship that we assess in the first step is crucial to projections of variables from anticipated climate change over the next 100 years. However, the identification of effects from temperature anomalies requires strong assumptions about adaptation and mitigation as well as the persistence of temperature responses of macroeconomic variables.[2] Third, we estimate how these temperature-induced variables will modify the required monetary policy for each euro area member country in the future. Finally, we analyze the gap between the average monetary policy required by euro area countries and the country-specific

[2]This is explained by the fact that, in the case of climate change, the past cannot be a relevant guide for the future since the climate-economy relationships might change over time.

required monetary policy, that is, the temperature-induced monetary stress. Our findings reveal that there are significant differences between euro area countries in the way macroeconomic variables respond to temperature anomalies, hence the significant divergences in the temperature-induced changes in inflation and GDP per capita over the period 2025-2100 within the currency union. This might be explained by the different size and composition of the economies composing the euro area, as well as the resilience of institutions and physical infrastructure. As a result, the accommodative magnitude of the required monetary policy to face these temperature-induced shocks differs among euro area countries. These discrepancies in the temperature-induced counterfactual rates give rise to a monetary stress that worsens over time, in particular when the climate scenario is the most pessimistic.

Overall, the existence of a (growing) temperature-induced monetary stress within the euro area constitute a challenge for the sustainability of the currency union and the *one size fits all* ECB's policy. Specifically, the differences in the required monetary policy among euro area countries make it difficult for the central bank to achieve its mandate of price stability, which will exacerbate welfare disparities within the euro area and, ultimately, fuel anti-EU sentiment

The following section exposes the related literature. Section 3 analyzes the impact of temperature anomalies on the macroeconomic objectives of the ECB, inflation and economic growth. Section 4 measures the stress of living in a monetary union under temperature-induced shocks. We further analyze several extensions to our main scenario in Section 5. The final section concludes the analysis.

2 Literature review

This research stands at the crossroads of two strands of literature : the impact of temperature anomalies on macroeconomic variables and the monetary stress of living in a currency union.

The first literature deals with the impact of temperature anomalies on inflation and GDP growth. Interestingly, while studies looking at the impact of climate change on GDP date back to the 2000s, those investigating the nexus between climate change and inflation are more recent. As a case in point, Faccia et al. (2021) analyse the impact of country-specific summer temperature anomalies on inflation for 34 advanced economies and 15 emerging and developing economies over the period 1980-2018. They find evidence that extreme temperatures have long-lasting effects on inflation, in particular for emerging market economics when the shock occurs in the summer. Following this line of thought, Mukherjee and Ouattara (2021) assess the response of inflation to temperature shocks for a set of developed and developing countries over a relatively long period (1961-2014). Their findings suggest that temperature shocks lead to persistent inflationary pressures for developing countries. Using a sample of countries with different level of development and monetary regimes, Kabundi et al. (2022) find that the impact of temperature shocks on inflation depends these factors. Specifically, inflation tends to decline in advanced economies following a temperature shock in the medium term, while in the short term, inflation is generally well anchored thanks to central banks' credibility. Natoli (2023) constructs temperature shocks from the 1970s up to the end of 2019 to explore their effects on the US economy. He finds that unfavorable temperature surprises have a significant negative effect on the consumer price index. Focusing on the euro area, Ciccarelli et al. (2023) investigate the effect of weather shocks on inflation using indicators based on high-frequency meteorological data and inflation rates disaggregated by type of product. They find heterogeneous and asymmetric effects within the monetary union of weather shocks on inflation, depending on the country, the HICP component and the season. These different results highlighted by the literature might be explained by the numerous channels through which temperature anomalies affect inflation. On the supply side, the decline of agricultural productivity from droughts can lead to higher food prices, while the negative impact of heat on labor productivity, through increased mortality and morbidity for instance, can shrink the level of prices (Deryugina and Hsiang, 2014; Somanathan et al., 2021). On the demand side, higher temperature anomalies can discourage open air activities, which could reduce time allocated to outdoor leisure and shop retail sales (Tran, 2022) and thus, put downward pressure on consumer price levels. Regarding economic growth, Dell et al. (2012a) construct temperature and precipitation data for each country over the period 1950-2003 to anzlyze how changes in these climate variables affect economic growth. They find that only poor countries are negatively affected by higher temperatures. Burke et al. (2015) find increased temperature to have a negative effect on GDP growth but do not find differentiated impacts between rich and poor countries. Colacito et al. (2019) find that seasonal temperatures, particularly summer ones, have significant and systematic effects on the U.S. economy. Kahn et al. (2021) find evidence that a positive (or negative) climate shock has a long-term negative effect on per capita GDP growth, with marginal effects larger in low-income countries. De Bandt et al. (2021) evaluate the impact of temperature change on 126 low and middle income countries over the period 1960-2017. They find that a 1°C increase in temperature lowers annual growth in real GDP per capita by 0.74 to 1.52 percentage points. Berg et al. (2023) also find an impact of high temperatures on GDP. They show that the sign of the impact differs from one country to another, and in particular between developing countries (for which they find a positive impact) and the developed ones (for which a negative impact is found). This well documented negative relationship between higher temperatures and economic output can be explained by several mechanisms. At the microeconomic level, temperature affects GDP through the heat stress channel that reflects physical and cognitive labor productivity. For example, Graff Zivin and Neidell (2014) show substantial reductions in labor supply on hot days in the industries with high exposure to weather, while Seppanen et al. (2006) document that performance at office tasks decreases at high temperature. At the macroeconomic level, channels such as damages to capital stocks, or changes in investment behavior explain the negative nexus between the growth rate of GDP and temperatures anomalies (Fankhauser and Tol, 2005; Moore and Diaz, 2015; Acevedo et al., 2020). Finally, Carlsmith and Anderson (1979) and Burke and Leigh (2010) suggest that political and social instability that follow from higher temperature may impede economic growth through lower factor accumulation and productivity growth, respectively.

The second literature our research is related with is the one on the stress of living in a monetary union and is relatively scarce. The expression of monetary stress has been coined first by Clarida et al. (1998) and used since by several authors who have explored the issue. In this literature, researchers estimate Taylor rules for the euro area and calculate the (implicit) policy weights for the different member countries. As an illustration, Sturm and Wollmershäuser (2008) study the appropriateness of the single monetary policy by calculating the country-specific monetary stress for the euro area countries. They conclude that economic cycles in the euro area will only converge if the smaller member countries are given more weight than is proportional. Following this line of thought, Quint (2016) shows that monetary policy stress within the euro area, in particular between the peripheral countries (Greece, Ireland, and Spain) and the rest of the euro area members, has been decreasing prior to the recent financial crisis

3 The impact of temperature anomalies on macroeconomic variables

3.1 Methodology

We estimate the response of euro area macroeconomic variables, inflation and GDP per capita, to temperature anomalies. We follow the literature (Faccia et al., 2021; Kabundi et al., 2022; Natoli, 2023; Cevik and Jalles, 2023) and use local projections à la Jordà (2005) for the period 1996-2021. This approach is more flexible since it does not impose the dynamic restrictions embedded in vector autoregressions for instance. For inflation, we estimate the following specification:

$$ln(P_{c,m+h}) - ln(P_{c,m-1}) = \beta_c^h Temp\_anomaly_{c,m} + \sum_{n=1}^{6} \gamma_n^h \delta ln(P_{c,m-n}) \epsilon_{c,m} \qquad (1)$$

where $ln(P_{c,m+h}) - ln(P_{c,m-1})$ reflects the cumulative change in prices between horizons $m+h$ and $m-1$, which is defined as the difference in the natural logarithms of $P_{c,m}$.[3] c is the country index, m stands for the time index with monthly frequency and the horizon h takes values between 0 and 24. We include 6 lags of the dependent variable to remove potential autocorrelation in the error term. $Temp\_anomaly_{c,m}$ represents the temperature anomaly, which we define more precisely below. Finally, we use Newey and West (1994) standard errors to control for heteroskedasticity and serial correlation in the idiosyncratic error term, ϵ.

To estimate the response of GDP per capita to temperature anomalies, the following specification is estimated:

$$ln(Y_{c,q+h}) - ln(Y_{c,q-1}) = \beta_c^h Temp\_anomaly_{c,q} + \sum_{n=1}^{2} \gamma_n^h \delta ln(Y_{c,q-n}) + \epsilon_{c,q} \tag{2}$$

where $ln(Y_{c,q+h}) - ln(Y_{c,q-1})$ is the cumulative change in real GDP per capita between horizons $q+h$ and $q-1$. The right-hand variables are similar to eq. (1) except that the time index q is at a quarterly frequency. As a result, the horizon h takes values between 0 and 8 while we include 2 lags of the dependent variable in the model.

In both models, impulse response functions are defined by the sequence of the coefficients of interest, the β^h, that measure by how much prices and GDP per capita react following an increase in temperature anomaly by 1°C for every country c at every horizon h.

3.2 Data

To study the effect of climate shocks on economic variables, the literature usually uses the concept of temperature anomalies, comparing temperatures to the average ones known in a specific reference period. Hansen and Lebedeff (1987) suggest that temperature anomalies are more suited to measure the impact of climate change given the difficulty to measure absolute temperatures, due to the fact that they vary considerably over short

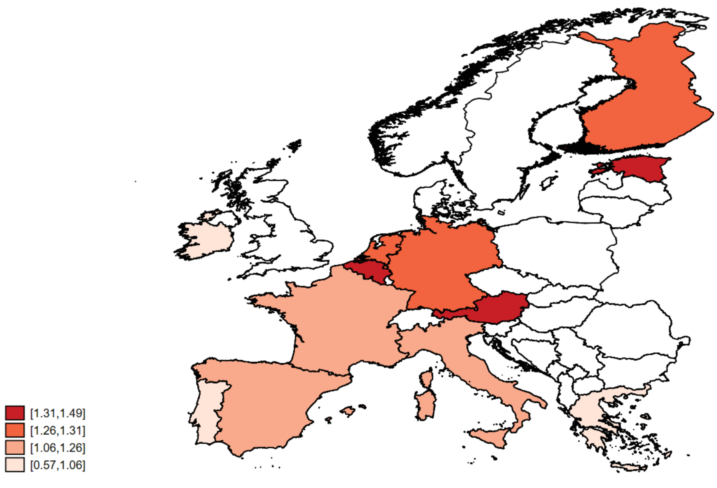
[3] The use of a log transformation makes the interpretation of the unit root in the level variables straightforward (Fomby et al., 2013).

distances. Following this line of thought, we retrieve temperature data at the country level from the World Bank Climate Change Knowledge Portal. To measure temperature anomalies, we follow the Food and Agriculture Organization of the United Nations which considers the period 1950-1980 as reference. As a result, the temperature anomaly of country c in month m, $Temp\_anomaly_{c,m}$, is measured as:

$$Temp\_anomaly_{c,m} = Temp_{c,m} - \overline{Temp}_{c,m} \tag{3}$$

where $Temp_{c,m}$ is the monthly average temperature of country c in month m and $\overline{Temp}_{c,m}$ the average temperature of country c in month m during the reference period 1950-1980. Figure 1 shows the average monthly temperature anomaly of euro area countries in the period 1996-2021. Northern and core European countries have had the highest monthly average temperature anomaly throughout that period, followed by Southern European countries. Hence, the maps reveals a large degree of heterogeneity among euro area countries which may create an issue for the definition of a single monetary policy if the temperature anomalies have macroeconomic consequences.

Figure 1: Average monthly temperature anomaly in euro area countries (1996-2021)



As a next step, since our objective is to measure the monetary stress induced by temperature anomalies in the euro area, we focus on the two variables of interest for the ECB, namely, inflation and output. Specifically, we use monthly data of the harmonized index of consumer prices (HICP) for our sample of euro area countries in the period 1996-2021.[4] The advantage of using the HICP is that they are based on harmonised statistical methods, which makes cross-country comparisons possible. For output, we follow the literature and we rely on the quarterly chained volume estimates of GDP per capita to measure the impact of temperature anomalies on economic activity (Dell et al., 2012b; Colacito et al., 2019; Newell et al., 2021; Kalkuhl and Wenz, 2020)). Hence, to estimate eq. (2), we sum the monthly temperature anomalies to obtain a quarterly variable. Data for both statistics are taken from Eurostat.

3.3 Results

Figures 2 and 3 show the responses of national inflation rates and GDP per capita, respectively, to an increase in the anomaly of the monthly mean temperature from its historical average by 1°C up to two years after the shock. Both estimates are carried out on the full sample, going from January 1996 to December 2021.

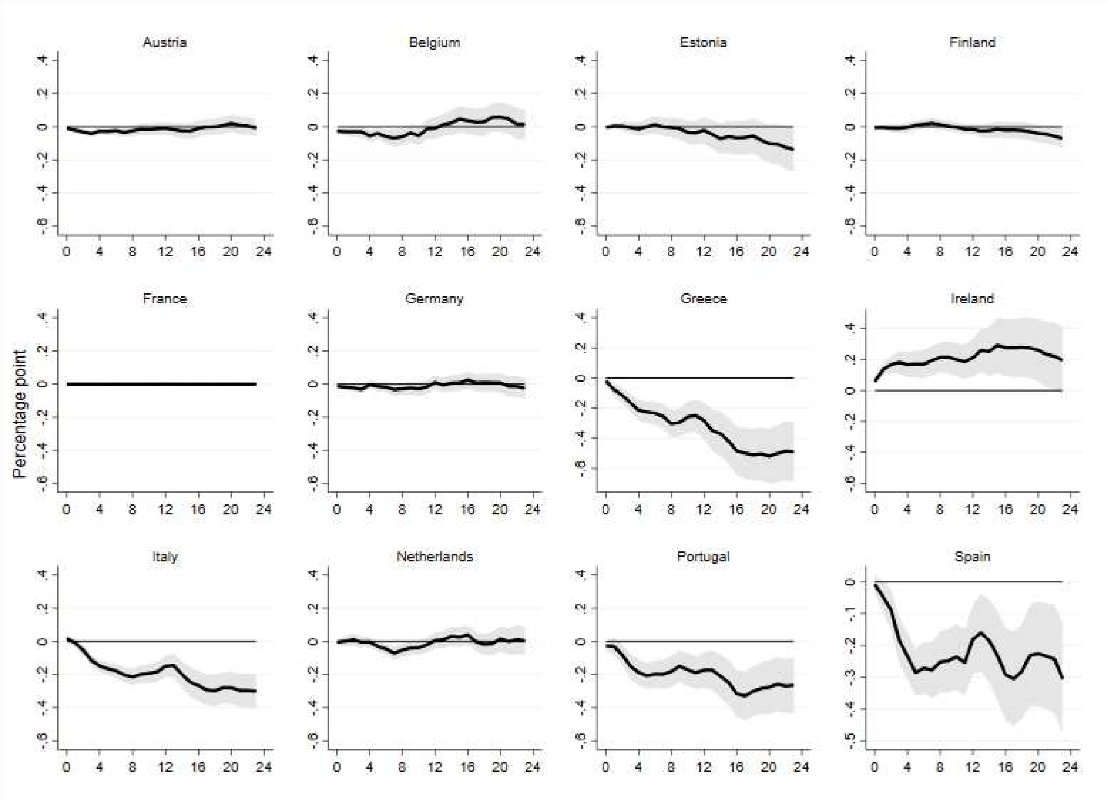
Regarding the impulse response function (IRF) of inflation, on the one hand, the most striking result is that the effect of temperature anomalies is not uniformly spatially distributed over the euro area countries. Countries from the South of Europe (Greece, Italy, Portugal and Spain) and the periphery (Estonia) are significantly and negatively affected by temperature anomalies. Specifically, after 24 months, the effect peaks to -0.2 percentage points (pp) for Estonia, -0.4 pp for Greece, -0.3 pp for Italy, Portugal and Spain. On the other hand, the response of inflation for countries from the core, such as Austria, Belgium, France, Germany and the Netherlands, is not significantly different from zero throughout the 24-month horizon. Interestingly, the positive trend of the IRF for Ireland might be explained by the fact that warming raises productivity in cooler countries (Burke et al., 2015).

[4] Austria, Belgium, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal and Spain.

The negative relationship between temperature anomalies and inflation observed for Southern European countries could be explained by at least three factors: (i) the reduction in the demand for heating during autumn and winter, (ii) the reduction in labor supply and productivity and (iii) the reduction in household demand in the retail and the real estate sectors (Starr, 2000; Ngai and Tenreyro, 2014). All these factors have been shown to induce downward pressures on prices (Auffhammer and Mansur, 2014; Dasgupta et al., 2021). Other factors, such as structural and demographic differences or fiscal and institutional capacity, may reflect the weaker capacity of Southern European countries to adapt to the consequences of temperature anomalies.

These results, of economically important size, are in line with studies that look at the effect of temperature anomalies on prices. For instance, using a panel covering 173 countries over the period 1970–2020, Cevik and Jalles (2023) find that following a temperature shock, headline inflation declines significantly until reaching its trough (3.5 pp) 4 years after the shock. Natoli (2023) finds that the consumer price index (CPI) in the United States decreases after a temperature shock. Faccia et al. (2021) show that for 48 advanced and emerging market economies, headline CPI falls following positive temperature anomalies during spring, while anomalies happening in summer have more persistent effect. Finally, Kabundi et al. (2022) find falling response of inflation to temperature shocks in advanced economies, in particular in the second year since the shock. All these results suggest that demand-side effects dominate over supply-side ones when analyzing the effect of temperature anomalies on inflation in euro area countries.

Figure 2: Effect of temperature anomaly on inflation rate (1996m1, 2021m12)

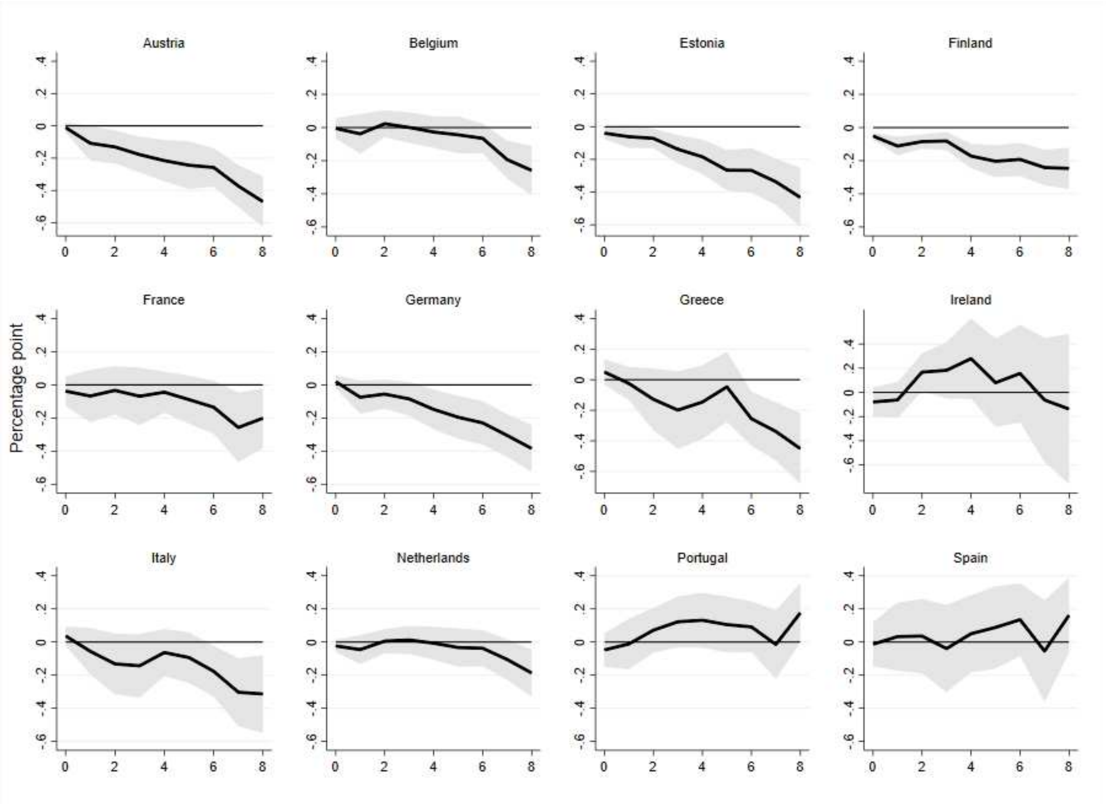


Note: The figures present impulse responses of national inflation rates to 1°C temperature anomaly. Time (horizontal axis) is in months. Gray–shaded areas indicate 68% confidence bands.

Figure 3 shows that temperature anomalies negatively and significantly affects GDP per capita in several European countries. The growth deceleration reaches a through 24-months after the shock, at which point real GDP per capita is lower in Austria (-0.5 pp), Belgium (-0.2 pp), Estonia (-0.4 pp), Finland (-0.2 pp), Germany (-0.4 pp), Greece (-0.5 pp) and Italy (-0.3 pp) than if the temperature anomaly had not happened. Again, these effects are economically important.

These findings are in accordance with the literature that looks at the temperature-GDP relationship. An an illustration, multiple studies find that a temperature shock is associated with a lasting reduction in the growth rate of GDP per capita (Dell et al., 2012a; Acevedo et al., 2020; Casey et al., 2023b). Specifically, Berg et al. (2023) find negative GDP responses to temperature shocks for rich countries in the medium and long horizons. For the United States, Natoli (2023) shows that real GDP significantly declines in response to a positive temperature surprise, with the effect reaching a trough between 1 and 2 years after the shock.

Figure 3: Effect of temperature anomaly on GDP per capita (1996m1, 2021m12)



Note: Note: The figures present impulse responses of national GDP per capita to 1°C temperature anomaly. Time (horizontal axis) is in quarters. Gray–shaded areas indicate 68% confidence bands.

4 The temperature-induced monetary stress

4.1 Expected climate warming and macroeconomic variables

We project the impact of expected warming on inflation and GDP per capita by 2100, using the coefficient estimates of the cumulative temperature-anomaly effects obtained from models (1) and (2) and the projected temperatures published by the IPCC in its sixth assessment report.

We use the temperature projections modeled in the Shared Socioeconomic Pathways (SSP) using the latest climate modelling – the sixth Coupled Model Intercomparison Project (CMIP6) – to measure projected temperature anomalies. Projected temperature anomalies are estimated by assuming a linear increase from the historical average to country-specific median temperature projections to 2100 obtained from five SSP. These five SSP are based on narratives that the world could take in terms of population, economic growth, education, urbanisation and the rate of technological development: (i) a world of sustainability-focused growth and equality (SSP1); (ii) a middle of the road scenario (SSP2); (iii) a fragmented world of resurgent nationalism (SSP3); (iv) a world of ever-increasing inequality (SSP4); and (v) a world of rapid and unconstrained growth in economic output and energy use (SSP5).[5] On the one hand, SSP1 and SSP5 convey optimistic trends for human development. However, while the latter assumes this will be driven by an energy-intensive economic framework, the former expects a shift toward sustainable practices. On the other hand, SSP3 and SSP4 are more pessimistic in their assessment of future economic and social developments. Finally, SSP2 represents a "middle of the road" scenario where trends broadly follow their historical patterns throughout the 21st century.

In line with the literature (Casey et al., 2023a; Dasgupta et al., 2021), we quantify the impact of future climate warming on inflation and GDP per capita by combining our estimated response function with the "middle of the road" scenario (SSP2). This approach, which assumes that future economies respond to temperature anomalies similarly to today's economies, should be taken with caution. Indeed, we consider that the impact coefficients estimated in our main analysis are stable over a future time period where there is no adaptation or mitigation. Moreover, we exclude from our analysis additional dimensions of rising temperatures that may also affect inflation and GDP per capita.[6] Nevertheless, Burke et al. (2015) find that neither technological advances

[5]For more details about the SSP narratives, see https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/.

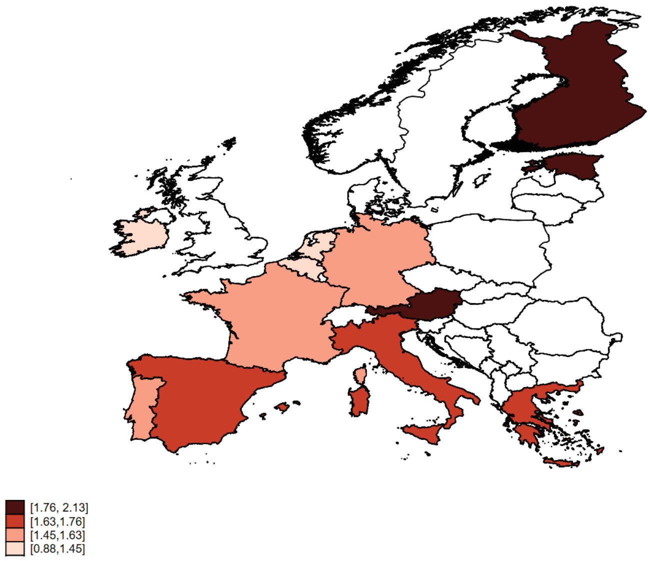
[6]These dimensions are, for instance, sea level rise, natural disasters, and loss of biodiversity.

nor the accumulation of wealth and experience since 1960 has modified the relationship between productivity and temperature or induced notable adaptation to climate change. First, for each euro area country, we compute the projected temperature anomaly, $Temp\_anomaly^{y}_{c,SSP2}$, as the anomaly of the projected annual temperature at year y for country c according to the SSP scenario 2, from its historical average (1995-2015):

$$Temp\_anomaly^{SSP2}_{c,y} = Temp^{SSP2}_{c,y} - \overline{Temp}_{c,(1995-2015)} \tag{4}$$

where $Temp^{SSP2}_{c,y}$ is the temperature projection at year y using the SSP scenario 2 for country c, and $\overline{Temp}_{c,(1995-2015)}$ the historical annual average temperature for country c. Figure 4 shows the projected average annual temperature anomaly between the two end points of our analysis, 2025 and 2100. The figure suggests that the countries that are most likely to experience the highest projected temperature anomaly according to the "middle of the road" scenario are Northern ones (Finland and Estonia) followed by Southern countries (Spain, Greece and Italy). Core European countries, in particular Belgium and the Netherlands, have the lowest projected temperature anomaly. Two things are worth noting here. First, the heterogeneity noted previously about the anomaly from the historical average is still present. However, and second, the countries that have known the largest historical anomalies are not necessarily the same who will suffer from large anomalies in the future.

Figure 4: Projected average annual temperature anomaly (2015-2100)



Next, we combine projected temperature anomalies with the impact coefficients which depict the cumulative effect of temperature anomaly on our variables of interest two years after, and with the upper and lower 68% confidence band for each estimated response function.[7] Hence, we compute the projected temperature-induced changes in inflation and GDP per capita over the period 2025-2100 for each euro area country c at each year y using the SSP scenario 2 as follows:

$$\hat{\pi}_{c,y}^{SSP2} = \beta_c^{24} \times Temp\_anomaly_{c,y}^{SSP2} \quad (5)$$

$$\hat{y}_{c,y}^{SSP2} = \beta_c^{8} \times Temp\_anomaly_{c,y}^{SSP2} \quad (6)$$

where $\hat{\pi}_{c,y}^{SSP2}$ and $\hat{y}_{c,y}^{SSP2}$ reflect the projected temperature-induced changes in inflation and GDP per capita over the period 2025-2100, respectively.

Figure 8 in the Appendix suggests that the magnitude of the effects of warming on inflation depends on the spatial location of countries. On the one hand, for Northern European countries (Austria, Belgium, France, Germany, Ireland, Netherlands), the projected temperature anomalies do not imply significant changes in inflation over time.

[7]Table 1 in the Appendix report the coefficients used for each euro area country.

On the other hand, Southern European countries experience a decrease in the level of prices over the next 100 years. Specifically, if climate projections are based on the "middle of the road" scenario, annual inflation is projected to decrease on average by 0.65 pp for Greece, 0.48 pp for Italy, 0.35 pp for Portugal and 0.40 pp for Spain.
Regarding the temperature-induced changes in GDP per capita, Figure 9 in the Appendix shows that the effect of projected warming is consistent among European countries, with only a few exceptions (Portugal and Spain). However, although there is a negative impact of projected warming on GDP per capita, its magnitude is different within euro area countries. Under the "middle of the road" scenario, the GDP per capita decrease goes from 0.84 pp (for Austria) to 0.12 pp (for Ireland).

4.2 A temperature-induced counterfactual policy rate

Since the objectives of the ECB is to maintain price stability and to ensure a balanced economic growth, we investigate the extent by which the policy rate should move in response to the persistent effect of temperature anomalies on inflation and GDP per capita. As a case in point, Natoli (2023) finds that the Fed reacts to temperature shocks by lowering policy rate.
We resort to a Taylor-type monetary rule which has been frequently used to measure ECB's reaction function (Sauer and Sturm, 2007). Taylor (1993) suggests that the interest rate behavior could be described with the following rule:

$$i_t = \overline{\pi} + \phi(\pi_t - \overline{\pi}) + \gamma y_t + R \tag{7}$$

where i_t is the target level of the short-term nominal interest rate, π_t is the inflation rate and $\overline{\pi}$ the target level of inflation, hence, $\pi_t - \overline{\pi}$ can be described as the inflation gap. y_t is the output gap and R the equilibrium level of the real interest rate. With ϕ

and γ equal to 0.5 and R to 2 percent,[8] the equation becomes:

$$\hat{i}_{c,y}^{SSP2} = 1.0 + 1.5\hat{\pi}_{c,y}^{SSP2} + 0.5\hat{y}_{c,y}^{SSP2} \tag{8}$$

where $\hat{\pi}_{c,y}^{SSP2}$ and $\hat{y}_{c,y}^{SSP2}$ reflect the projected temperature-induced changes in inflation and GDP per capita estimated in models (5) and (6), respectively. Given that the findings suggest a decrease in inflation and GDP per capita in response to projected temperature anomalies, this would imply significant downward move of the policy rate. However, asymmetries in the magnitude of the decline of inflation and GDP per capita observed in figures 8 and 9 will likely generate differences in the degree of policy rate fall among countries. In this context, eq. (8) allows to estimate the projected temperature-induced policy rate that should prevail for each euro area country during the period 2025-2100.

Figure 10 in the Appendix shows that most of the countries considered in our sample will need an accommodative monetary policy stance over the future, in particular Estonia, Greece and Italy. In contrast, other countries, such as Belgium or the Netherlands, do not require a significant change in the policy rate in response to the effect of projected temperature anomalies on inflation and GDP per capita. All in all, the large majority of countries in the sample (9 out of 12) will require a more accommodative monetary policy to face temperature anomalies in the future. However, the degree of monetary accommodation varies from one country to the other, which will make the monetary policy design task even more complex, as we will now measure.

4.3 A temperature-induced monetary policy stress

The divergent counterfactual policy rates observed in figure 10 imply that the single ECB monetary policy will not be appropriate for all member countries in the future. Hence, the "one-size fits all" policy will be even less relevant in the context of climate change. These divergences between the policy rates required by individual countries

[8] Even if the risks related to climate change may lower the equilibrium real interest rate, this doesn't affect our empirical framework (Bylund and Jonsson, 2020).

in response to the projected temperature-induced changes in inflation and GDP per capita will fuel political pressure on the ECB, since its policy is usually evaluated from a national rather than a European perspective. Following the literature (Sturm and Wollmershäuser, 2008), we refer to these divergences as country-specific monetary stress. In this paper, we define the monetary policy stress for an individual country c as the difference between its temperature-induced counterfactual policy rate and the average of the counterfactual rates of the rest of the countries – excluding country c. We measure the monetary stress for each euro area country c over the projected year y, $MS_{c,y}^{SSP2}$, as:

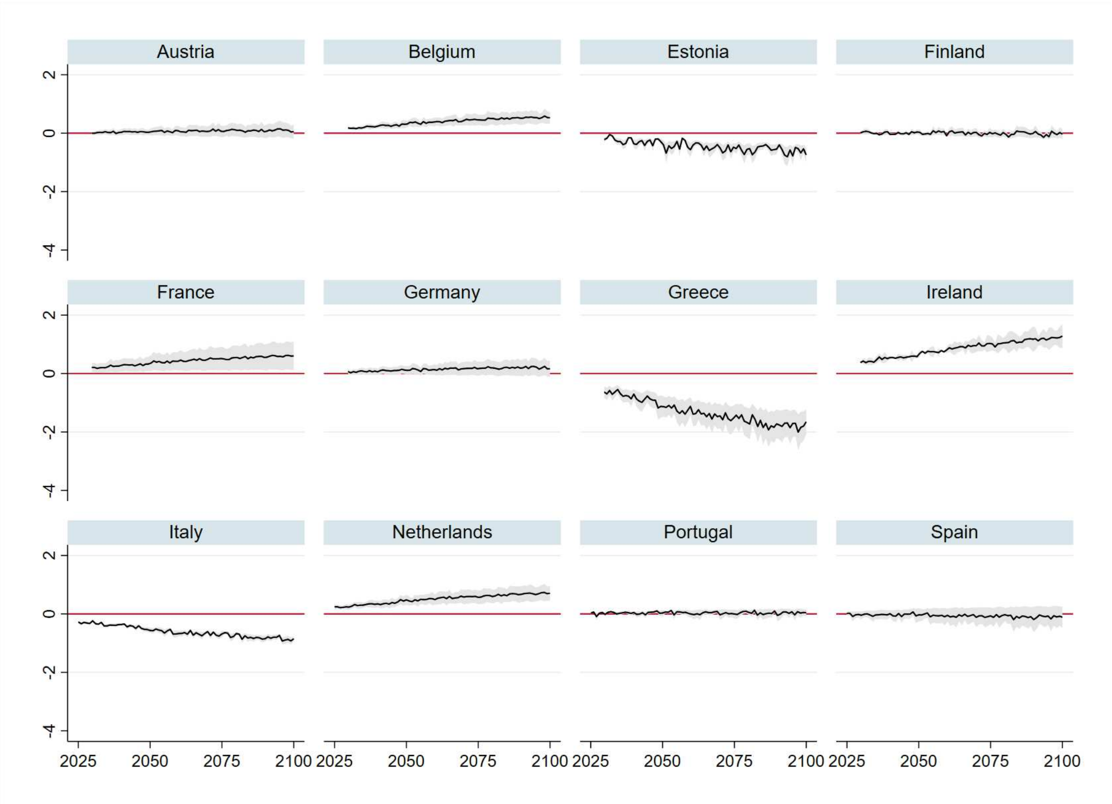
$$MS_{c,y}^{SSP2} = \hat{i}_{c,y}^{SSP2} - \bar{i}_{-c,y}^{SSP2} \tag{9}$$

where $\hat{i}_{c,y}^{SSP2}$ is the counterfactual rate measured for country c at the projected year y and $\bar{i}_{-c,y}^{SSP2}$ the average of the counterfactual rates of euro area countries excluding country c. On the one hand, a positive value for $MS_{c,y}^{SSP2}$ implies that the required monetary policy for country c is more hawkish than what is required for the other countries. If, on the other hand, $MS_{c,}^{SSP2}$ is negative, the required monetary policy for country c appears too accommodative for the other countries.

The results of the counterfactual exercises shown in Figure 5 are a reflection of the policy stress that the euro area is likely to face as a result of climate warming. The figure suggests a mixed picture in terms of monetary policy stress among euro area countries. While some countries from the South and the Periphery (Estonia, Greece, Italy) have a negative monetary stress, corresponding to a situation where they require a more accommodative monetary policy stance compared to the rest of the euro area, other countries have a positive monetary stress (Belgium, Ireland and the Netherlands), that is, they require a tighter monetary policy stance. Hence, by 2100, Estonia, Greece and Italy would require a policy rate lower by 100, 120 and 200 basis points, respectively, while Belgium, Ireland and the Netherlands would require a policy rate higher by 50, 90 and 65 basis points, respectively. Finally, only a few countries, most of them belonging to the core and the North (Austria, Finland, France, Germany, Portugal and Spain) have a monetary policy stress that is not quantitatively different from 0.

These findings are in contradiction with the traditional view from the literature on currency unions, which considers that countries with similar shocks should form a union. Our analysis reveals that this view is questionable in front of one of the aspects that climate change brings with it, i.e., temperature anomalies. These shocks are interacted with the structure of the euro area economies, and it is this interaction that generates our measure of stress. In some part, our measure of stress may even suffer from an underestimation bias, which would make matters worse, in the sense that temperature anomalies would strongly reduce the welfare gains of the monetary union.

Figure 5: Monetary stress of euro area economies (2025-2100)

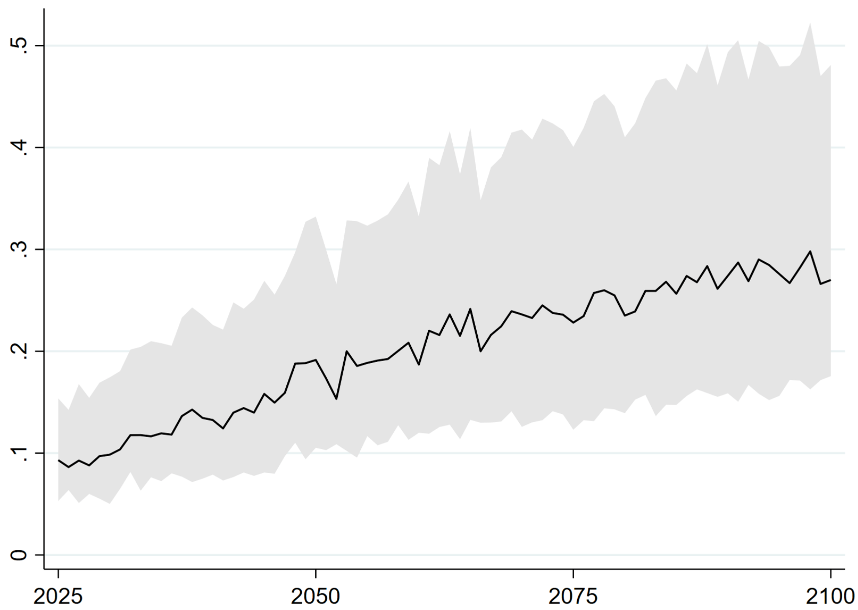


Note: The bold line is the projected monetary stress obtained with the SSP2's scenario while the shaded area is the interval estimation of projected monetary stress obtained with the upper and lower 68% confidence bounds for each estimated response.

As a final step, we aggregate the country-specific stress indicators to the euro area level.

For that purpose, we follow Sturm and Wollmershäuser (2008) and use a (i) GDP-weighting scheme and (ii) an absolute value to aggregate the individual stress measures. The aggregate stress measure is computed as $MS_{EA,y}^{SSP2} = \sum_c w_c|MS_{c,y}^{SSP2}|$, where w_c is the GDP-weight attributed to country c in the euro area. Figure 6 shows that the aggregate stress measure is likely to worsen over time, with a magnitude comprised between 0.2 and 0.5 pp by 2100.

Figure 6: GDP-weighted aggregate monetary stress (2025-2100)



Note: The bold line is the projected GDP-weighted aggregate monetary stress obtained with the SSP2's scenario while the shaded area is the interval estimation of the projected GDP-weighted aggregate monetary stress obtained with the upper and lower 68% confidence bounds for each estimated response.

Overall, our results reveal that there are large differences in terms of monetary policy needs for euro area individual countries, and that these differences are likely to increase over time, as the Figure 6 reveals. These heterogeneous monetary policy needs in response to climate warming will put an additional burden on the ECB's single monetary policy, and may constitute a challenge for the long-term sustainability of the euro area. Such results can only make more relevant the efforts made to mitigate the consequences of climate change. Although they are often considered from a microeconomic point of view and, for what concerns central banks, from the financial stability side, our results show that they also have important macroeconomic side effects, making it more urgent to deal with climate change.

5 Extensions and Robustness

5.1 Alternative Shared Socioeconomic Pathways

The results shown in section 4 are based on the "middle of the road" scenario (SSP2) and are thus likely to be different if we consider alternative climate scenarios. This observation is even more relevant given the large differences in the projected changes in temperature across the scenarios shown in Figure 11 in the Appendix. The CMIP6 model projects that under the SSP1, SSP2 and SSP5 scenarios, average temperature in the long term would increase by 0.36°C, 1.82°C and 4.37°C, respectively. Specifically, for our sample of countries, under the "middle of the road" scenario, the strongest increase would be in Finland while the smallest one would happen in Ireland. Regarding the most optimistic (pessimistic) scenario, the SSP1 (SSP5), the maximum increase in temperature would also occur in Finland while the minimum one would be Belgium (Ireland).

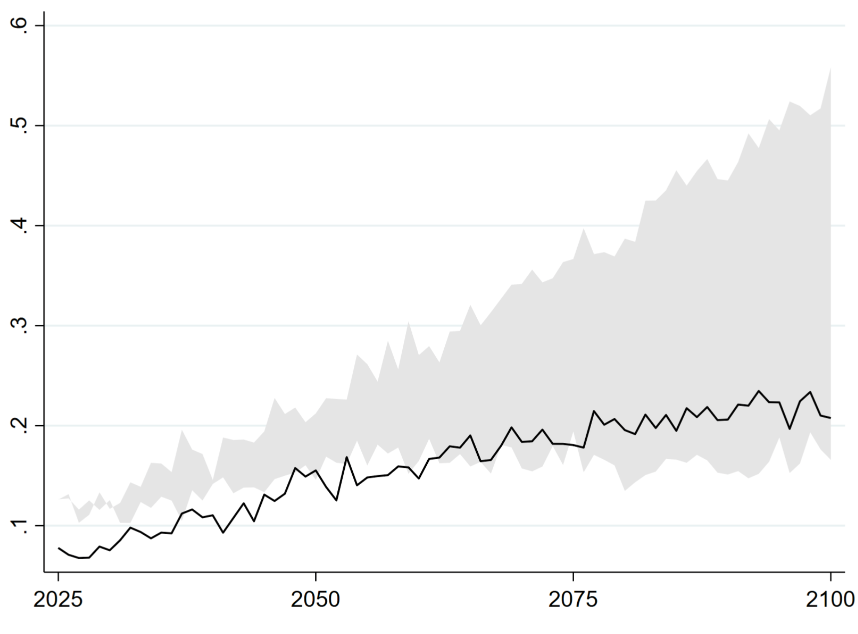
Against this background, we re-estimate eqs. (4)-(9) using the SSP1 and SSP5 scenarios to assess the interval of the temperature-induced changes in (i) inflation, (ii) GDP per capita, (iii) counterfactual policy rates and (iv) monetary stress among euro area countries.[9]

The simulations of the temperature induced-changes in inflation and GDP per capita obtained with the alternative scenarios are in line with those obtained with the baseline one, although the magnitude of the reduction is different. Indeed, under the more aggressive (accommodating) emission scenario, the SSP5 (SSP1) scenario, the annual average reduction in inflation is expected to be 1.2 (0.65) pp for Greece and 0.8 (0.37) for Italy, 0.5 (0.19) for Portugal and 0.6 (0.27) for Spain. The same observations can

[9]To save some space, the figures are not displayed and are available upon request.

be made for GDP per capita, for which the more dramatic scenario enlarges the range of reduction (from 1.28 to 0.22), while the most optimistic one reduces it (from 0.55 to 0.09). The interval of the decline of the counterfactual rate in most of the euro area countries is also consistent with the one obtained with the "middle of the road" scenario, but with a large range for South European countries such as Italy (from 0.22 to -0.61) or Greece (from -0.36 to -1.58), and a small one for Core European countries such as France (from 0.78 to 0.51) and Germany (from 0.76 to 0.45). Interestingly, when computing the temperature-induced monetary stress for individual countries, we observe that the degree of stress calculated with the SSP2 scenario is below those computed with the alternative scenarios. This confirms that the middle of the road scenario is the low-case one. This is confirmed by Figure 7, which shows the aggregate stress measures obtained with the three scenarios. For most of our sample period, the aggregate stress obtained with the SSP2 is lower than the interval of the stress obtained with the SSP1 and SSP5 scenarios.

Figure 7: GDP-weighted aggregate monetary stress (2025-2100)



Note: The bold line is the projected GDP-weighted aggregate monetary stress obtained with the SSP2 scenario while the shaded area is the interval estimation of the projected GDP-weighted aggregate monetary stress obtained with the SSP1 and SSP5 scenarios.

5.2 Controlling for precipitation anomalies

Beyond the impact of temperature anomalies on macroeconomics variables depicted in section 3.3, the literature has also found that precipitation anomalies affect inflation and economic growth (Kotz et al., 2023), mainly because floods and/or droughts imply agricultural losses and destroy infrastructure. Following this line of thought, Kabundi et al. (2022) find droughts to be inflationary in advanced economies while Dell et al. (2012b) show evidence that changes in precipitation have small and negative effect on economic growth in rich and poor countries.

We test the robustness of our findings by including precipitation anomalies of euro area countries in eqs. (1) and (2). We measure precipitation anomalies the same way as temperature anomalies, that is, by taking the difference of precipitations between a specific month comprised in the period 1996-2021 and the average precipitation in the same month over the period 1950-1980. We find that in our sample period (1996-2021) southern countries had, on average, a negative precipitation anomaly while northern countries had a positive one. The IRFs show that even when controlling with precipitation anomalies, the impact of a 1°C temperature anomaly on inflation and GDP per capita is similar, in terms of magnitude and significance, to the baseline ones.[10] These results show that the effect of temperature anomalies on the macroeconomic variables is robust beyond the precipitation anomalies that might occur at the same time.

5.3 Adaptation to temperature anomalies

There might be a gradual adaptation process of the economic system to higher temperatures. For instance, Mendelsohn and Nordhaus (1996) suggest that it is possible for agriculture to adapt to changes in climate by planting different crops. Therefore, we construct a new measure of temperature anomaly defined as the temperature deviation of a specific month from the monthly average temperature starting in 1980 and ending one year before, instead of the 1951-1980 average. For instance, temperature anomaly of January 1998 is measured as the difference between the temperature deviation of this

[10] To save some space, the IRFs are available upon authors' request.

month from the average temperature of January from 1980 until 1997. This procedure allows to consider possible adaptation to increasing warm temperatures recently.
We replace the temperature anomaly measured with eq. (3) with the new one and re-estimate models (1) and (2) accordingly. The IRFs depicting the impact of a 1°C temperature anomaly on inflation and GDP per capita are in line, in terms of magnitude and significance, with those of the baseline model. This shows that the potential adaptation process does not alter the impact of temperature anomaly on macroeconomic variables.

6 Conclusion

In this paper, we provide evidence of the existence of a temperature-induced monetary stress in the euro area. This stress appears as a result of the asymmetric effects of temperature anomalies on inflation and GDP per capita within the currency union. Those asymmetries imply that the monetary policy needs for individual countries to achieve price stability will diverge over time, hence the presence of a temperature-induced monetary stress. Interestingly, we show that the degree of stress changes depending on the climate scenario and that it worsens when the climate scenario is more pessimistic.

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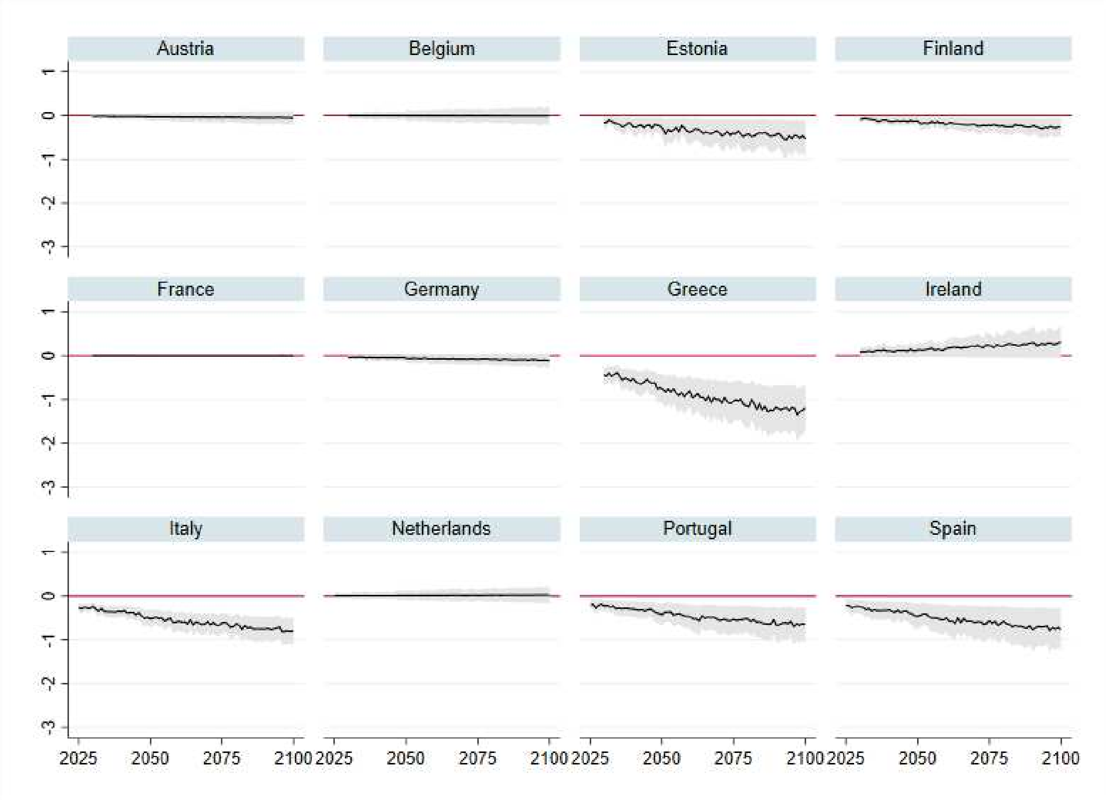
Appendix

Table 1: 2-year cumulative effect of temperature anomaly on inflation and GDP per capita

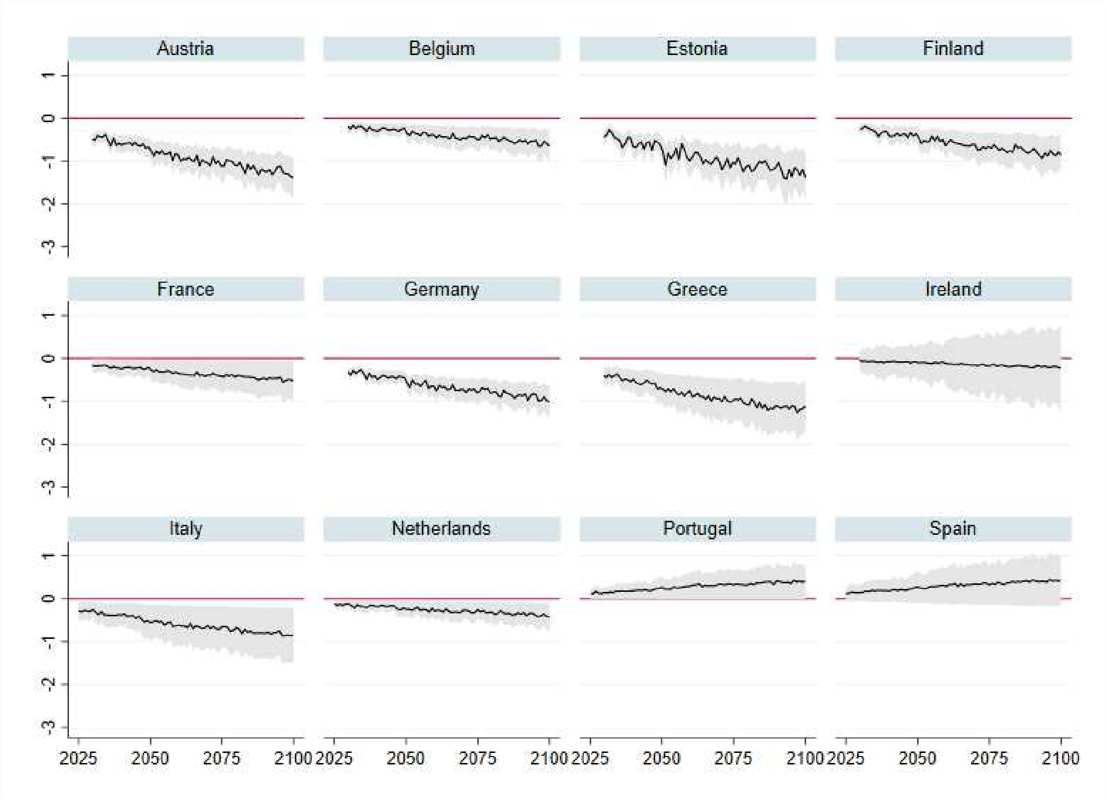
Country	Inflation	GDP per capita
Austria	0,0069743	-0,4695802
Belgium	-0,0002493	-0,2587495
Estonia	-0,1510064	-0,4326935
Finland	-0,0666084	-0,2465675
France	-0,0636513	-0,2011965
Germany	-0,0195247	-0,3843606
Greece	-0,3789182	-0,4510485
Ireland	0,0663101	-0,1377134
Italy	-0,2787566	-0,3133269
Netherlands	0,0096166	-0,1869576
Portugal	-0,2413174	0,1762825
Spain	-0,2386734	0,1618944

Figure 8: Temperature-induced changes in inflation for each euro area economy (2025-2100)



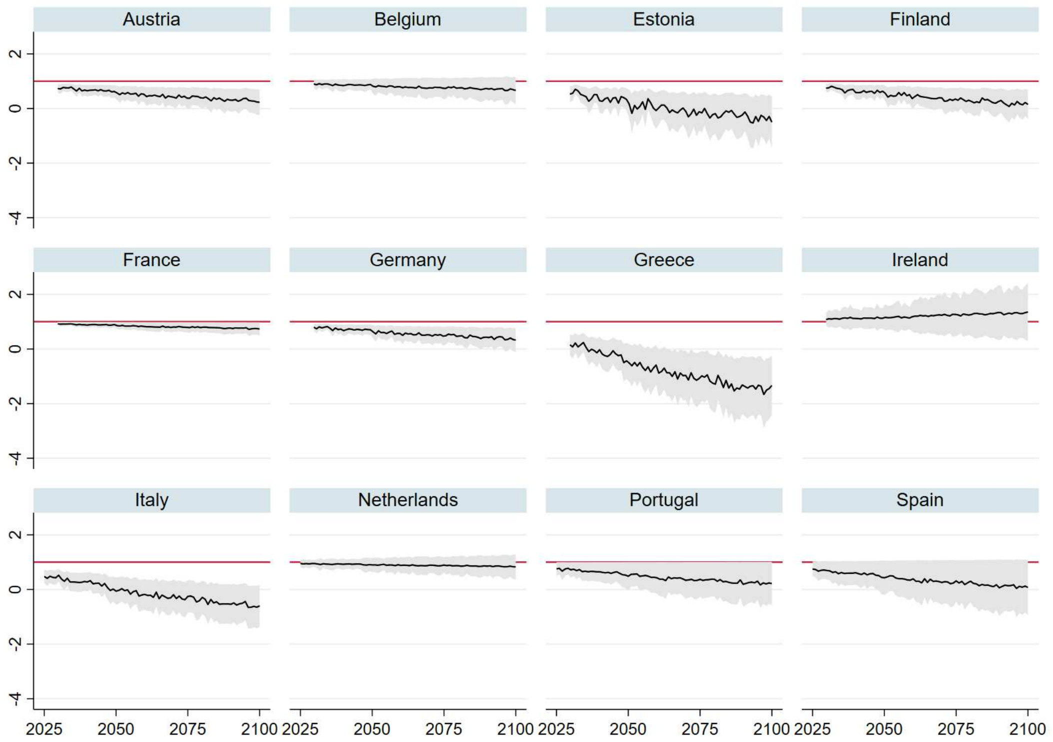
Notes: The bold line is the projected inflation rate obtained with the SSP2 scenario while the shaded area is the interval estimation of projected inflation rate obtained with the upper and lower 68% confidence bounds for each estimated response.

Figure 9: Temperature-induced changes in GDP per capita for each euro area economy (2025-2100)



Note: The bold line is the projected GDP per capita monetary stress obtained with the SSP2 scenario while the shaded area is the interval estimation of GDP per capita obtained with the upper and lower 68% confidence bounds for each estimated response.

Figure 10: Temperature-induced changes in policy rate for each euro area economy (2025-2100)



Notes: The bold line is the projected counterfactual policy rate obtained with the SSP2 scenario while the shaded area is the interval estimation of counterfactual rater obtained with the upper and lower 68% confidence bounds for each estimated response.

Figure 11: Projected changes in temperatures (2025-2100)