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HIGH TEMPERATURE SHOCKS ARE SUPPLY SHOCKS. EVIDENCE FROM ONE CENTURY OF MONTHLY DATA

Abstract

Are temporary high-temperature anomalies supply or demand shocks? And how do central banks respond to them? We investigate these questions with a new historical dataset covering 14 European countries over a full century and accounting for nonlinearities via state-dependent impulse response functions in the vein of Auerbach and Gorodnichenko (2012). The following stylized facts emerge: 1) a high temperature shock is a negative supply shock (lower output growth and higher inflation); 2) the impact is usually less pronounced - but more persistent - on inflation than on output; 3) central banks have responded to these shocks by lowering their interest rate; 4) the macroeconomic impact of individual high temperature shocks on inflation has diminished over time, but the frequency of these shocks has increased.

JEL Classification: N/A

Keywords: Supply shocks, Climate shocks, Climate change mitigation, Climate policy, Monetary policy, Inflation

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Climate change is one of the major challenges of our time, requiring action to halt global warming and alleviate its consequences.The consequences of climate change have been visible for several decades, and are becoming more pronounced every year, with rising global temperatures and an increasing number of extreme events (IPCC, 2023). Among these extreme events, periods of abnormally high temperatures (i.e. *high temperature shocks*) have become more frequent, and this trend is set to continue in the future.

A key question for economists and policymakers is to assess the effects of high temperature shocks on the key economic variables which are the focus of macroeconomic policies. In particular, monetary policy is now recognized as crucial to stabilize business cycle fluctuations, that is maintaining inflation close to the target while minimizing the output gap. Central bankers themselves have therefore expressed concerns about whether the increased frequency and amplitude of climate shocks could create new trade-offs for monetary policy (e.g. Cœuré (2018)).[1]

If high temperature shocks are becoming more frequent, what are the implications for monetary policy? The response to this question depends on the impact of these shocks on inflation and output growth. First, it is important to know if these shocks indeed have an effect on business cycles. This is not a trivial task. Some research has emphasized the adaptation of households and companies to temperature shocks, suggesting that societies might be more resilient to temporary heat waves, especially for non-agricultural production (Deschenes (2014); Kahn (2016); Lai, Li, Liu, and Barwick (2022)). Second, just like for other types of shocks in the economy (e.g. Baqaee and Farhi (2022); Guerrieri, Lorenzoni, Straub, and Werning (2022)), it is essential for policy-makers to know if temporary high temperature anomalies are demand shocks or supply shocks. Only the later type of shock creates a trade-off for monetary policy because supply shocks increase inflation while decreasing production.

We address these questions using monthly data covering 14 European countries since 1920. We restrict ourselves to measuring the impact of above-average summer temperature increases (i.e. 'temperature anomalies'), because our research aims to assess the potentially destabilizing effects of the highest temperature shocks. We reach the following conclusions.

[1]In this 2018 speech, Benoit Coeuré, former member of the board of the European Central Bank argued: "I will argue that climate change can be expected to affect monetary policy one way or the other. That is, if left unchecked, it may further complicate the correct identification of shocks relevant for the medium-term inflation outlook, it may increase the likelihood of extreme events and hence erode central banks' conventional policy space more often, and it may raise the number of occasions on which central banks face a trade-off forcing them to prioritise stable prices over output."

1) a high temperature shock in the summer months is a negative supply shock (lower output and higher inflation); 2) the impact on prices is usually more persistent but less pronounced than on output; 3) central banks have responded to these shocks by lowering their interest rate; 4) the macroeconomic impact of individual high temperature shocks on inflation has diminished over time, but their frequency has increased. Taken together, these four results underline the fact that the increasing frequency and amplitude of extremely hot weather is creating difficult trade-offs for a central bank whose objective is to stabilize both output and inflation.

The economic impact of temperature shocks is quantitatively substantial. On average, since 1920, a temporary monthly temperature rise of 1°C (above a threshold of 1°C relative to the average summer temperature) temporarily reduces output growth by 1pp, increases the inflation rate by 0.4pp and, in response, causes the central bank rate to fall by 40bp. This is not trivial, since such monthly shocks have occurred on average twice a year in recent times. It should be noted, however, that in the estimates from 2000 onwards, there is no longer any effect on inflation for shocks above a threshold of 1°C relative to the average summer temperature. But there is still a positive effect on inflation of 0.2pp for increases of 1° above a threshold of 2°C. These events - anomalies above 2°C - were very rare in the past, but now occur more than once a year (see our conclusion and figure 18).

The impact of temperature shocks on macroeconomic policies and short-term fluctuations is different from the question of the long-term impact of climate change on long-run growth and standards of living (see e.g Dell, Jones, and Olken (2012); Berg, Curtis, and Mark (2023); Kotz, Wenz, Stechemesser, Kalkuhl, and Levermann (2021); Bilal and Känzig (2024); Kotz, Levermann, and Wenz (2024) for analyses of the impact of higher temperatures on long-run growth). They require different data and methodology. For our purpose, it is especially crucial to have data that can track fluctuations within a year and to account for non-linearities. Indeed, the fact that extreme temperature shocks are rare events (although they might become more frequent in the future) and that the effects of temperatures on the economy are non-linear raises important econometric challenges. It restricts dramatically the number of relevant observations in the past.

To cope with the low number of past temperature shocks, non-linear effects, and achieve a sufficiently high number of observations, we have built a new historical dataset and we apply a new methodology to estimate the effects of temperature shocks. As we will show, hot temperature anomalies existed throughout the 20th century and only very recently became more frequent.[2] We take non-linearity into account by using state-dependent local projections with a smooth threshold that allow to exploit the full distribution of temperature anomalies above a certain threshold. This is also a way to increase the number of observations, as explained by Auerbach and Gorodnichenko (2012): observations just below the threshold are incorporated with a lower weight (probability). This method also makes the results less sensitive to the choice of given threshold. Auerbach and Gorodnichenko (2012)'s methodology has a number of advantages compared to several other approaches recently followed in the literature on the economic effects of temperature shocks. In particular, a state-dependent estimate accounting for continuous temperatures is more precise than if the temperature anomaly is measured as the number of days above a certain threshold (as in Natoli (2024)). It allows us to focus on the largest shocks and take their size into account.

Monthly temperature data are taken from the Berkeley Earth project (Rohde and Hausfather, 2020) and aggregated at the national level. Monthly data on industrial production, consumer prices and central bank interest rates were collected for a companion project on historical central bank policies (Bazot, Monnet, and Morys, 2024). As usual in historical studies as well as in studies on more recent periods examining the short-term impact of monetary policy (Coibion (2012); Jarociński and Karadi (2020); Miranda-Agrippino and Ricco (2021); Bauer and Swanson (2023)), industrial production is used to proxy short-term output fluctuations. It has been shown that industrial production is the best tracker of quarterly real GDP, even in countries where the manufacturing sector is a small share of total value added (Romer and Romer (2017); Monnet and Puy (2021)).[3] Our study focuses on a group of countries with relatively similar weather and economic conditions work. This makes the econometric

[2] Another way of increasing the number of relevant observations (high temperature anomalies) is to construct a panel with a large number of countries, as in the Kotz, Kuik, Lis, and Nickel (2024) study on inflation rates from the 1990s. But this results in a panel of countries with very different weather and economic conditions, which gives rise to other types of non-linearities. In contrast, our study focuses on a group of countries with relatively similar weather and economic conditions. In the last section of the paper, we will examine how our results are affected by the countries in our sample whose weather conditions differ more from the average of our sample. As we explain below, our choice of countries is motivated not only by the homogeneity of weather and economic conditions, but also by the availability of historical monthly data on production and prices. The European countries are also small enough to avoid weather conditions in the same month being completely different from one part of the country to another, as can be the case for the United States, India, China or Russia.

[3] No GDP data exists at the monthly frequency. In European countries, monthly production and price indices started to be built after the First World War, which explains why our estimation sample starts in 1920 and covers only European countries.

modeling and the interpretation of the results easier, but it also means that temperature shocks are highly correlated between countries. The shock may be a common one, amplified by the correlation between countries (as discussed in Bilal and Känzig (2024)). Thus, we need to correct the standard errors for the correlation between countries using the procedure of Driscoll and Kraay (1998). Our estimations also include country-fixed effects and we use year-on-year growth rates and monthly dummies to avoid our results from being biased by regular seasonal fluctuations.

A key insight from our estimations is that the effects of high temperature shocks on macroeconomic variables are better observed when the average summer high temperature anomaly is large enough. When displaying our main results, we therefore first restrict our sample to countries where this is the case. The reason for restricting our sample to these cases - and thus highlighting significant effects - is that we know that average temperature and average temperature anomalies are bound to rise over the next few decades (Kharin, Flato, Zhang, Gillett, Zwiers, and Anderson (2018); Domeisen, Eltahir, Fischer, Knutti, Perkins-Kirkpatrick, Schär, Seneviratne, Weisheimer, and Wernli (2023)). Our benchmark sample is thus composed of Austria, Belgium, Germany, the Netherlands, Switzerland, France, Portugal, Spain and Italy.[4] As a robustness check, we add five countries with lower average hot anomalies (England, Denmark, Sweden, Norway, Finland). In this case, the period-by-period results display a lower and less significant effect of temperature shocks, although the results over the full sample (1920-2019) still hold.

An important finding of our estimations is that the effect of high temperature shocks on inflation is less strong (four times lower) in the recent decades than in the 1920-2019 sample average. By contrast, the responses of production show similar orders of magnitudes. Yet, while shocks above a 1 degree threshold no longer have significant effect on prices over the recent period (2000-2019), shocks above a 2 degree threshold still do. These results might simply reflect that, as it is well-known, the inflation rate has been less volatile in recent decades since the late 1990s, before the Covid period. It also suggests that, as far as consumer prices are concerned, economies seem to be more able to cope with hot temperature shocks than in the past, for example because food prices have a lower weight in today's consumer prices or because some jobs are less affected by supply side or labor disruption caused by hot weather.

[4] Note however that monthly production data are not available for Portugal, Spain and Italy during the interwar period, so that these countries are excluded from the estimation sample before World War II.

Relationship to the literature

There is now a large literature that has documented a negative effect of higher temperatures on economic growth but this literature has mainly focused on long-term effects (e.g. Dell, Jones, and Olken (2012); Kotz, Wenz, Stechemesser, Kalkuhl, and Levermann (2021); Bilal and Känzig (2024)), usually relying on annual data in a cross-country setting. Using similar methods and annual data, Mukherjee and Ouattara (2021) also finds that higher temperature is associated with higher inflation.

Numerous empirical microeconomic studies (see below) covering different countries and time periods have shown that temperature shocks have a negative impact on output and raise consumer prices. However, to the best of our knowledge, we are the first to identify these short-term effects at the macroeconomic level for a large sample of countries covering a full century. The empirical literature has generally focused on certain sectoral or regional effects and has not examined output in conjunction with prices. It is therefore far from clear that the effects will be transmitted to the general price index or to a general measure of output, especially in the short term. All the more so since a hot temperature shock may be a negative supply shocks on production (in the agricultural sector, for example) that could in principle be offset by positive demand shocks on others (energy - air conditioning - or water consumption, for example). And trade flows can also, in theory, help to smooth some of the short-term effects on national production and prices.

The literature on the impact of temperature shocks has identified two main channels through which they affect the economy. The first is through the agricultural sector. Weather shocks affect crop yields, harvests and hence agricultural production. The negative effect has been found in many countries, including advanced economies.[5] All of these papers identify non-linearities, with higher temperatures having a disproportionate effect on agricultural production and leading to higher agricultural prices. Several papers have also examined how shocks to agricultural sectors are then transmitted to the rest of the economy (e.g. De Winne and Peersman (2021); Kotz, Kuik, Lis, and Nickel (2024) on consumer prices). Based on an empirical study of New Zealand, Gallic and Vermandel (2020) builds a general equilibrium model that explains how weather shocks are transmitted through the agricultural sector to the rest

[5] This includes the following studies: Schlenker and Roberts (2009); Ciscar, Iglesias, Feyen, László, Regemorter, Amelung, Nicholls, Watkiss, Christensen, Dankers, Garrote, Goodess, Hunt, Moreno, Richards, and Soria (2011); Bremus, Dany-Knedlik, and Schlaak (2020); Ali, Kuriqi, and Kisi (2020); Crofils, Gallic, and Vermandel (2024); Lobell, Schlenker, and Costa-Roberts (2011); Burke and Emerick (2016).

of the economy (production, consumption, prices). The second channel is through labour productivity, which can be modified by weather conditions. (Seppanen, Fisk, and Faulkner, 2003) found that a 1°C increase in temperatures above 25°C would lead to a reduction in labour output of around 2%. Other studies show that extreme temperature shocks reduce hours worked and labour supply, including (Graff Zivin and Neidell, 2014); Deryugina and Hsiang (2014); Kalkuhl and Wenz (2020); Cachon, Gallino, and Olivares (2012) or Huppertz (2024).

A key question in the literature on agricultural and labor productivity channels is the extent to which economies have been able to adapt to higher temperature shocks over time. The evidence is mixed in this respect and remains subject to debate (e.g. Deschenes (2014); Kahn (2016); Burke and Emerick (2016); Zhang, Deschenes, Meng, and Zhang (2018);Lai, Li, Liu, and Barwick (2022)). Our main contribution to this question is to highlight that the macroeconomic impact of individual temperature shocks on consumer prices has decreased over the century, but their frequency has increased. It is beyond the scope of this paper to discuss which effect will dominate in the future, but these countervailing effects should be highlighted.

Contributions closer to ours are more recent and follow the rising attention expressed by central banks about how they should react to potential price increases due to climate shocks. Ciccarelli, Kuik, and Hernández (2024) look at the short-term response of inflation to high temperature anomalies in euro area countries since 1998 using monthly data and Bayesian VARs. Like us, they find that high temperature anomalies during the summer (only) have a positive effect on the inflation rate (see also Faccia, Parker, and Stracca (2021)). Kotz, Kuik, Lis, and Nickel (2024) also find a positive impact on inflation of a 1°C increase in monthly temperature in a panel of 121 countries since 1996 with monthly data. A key message of their paper is that the response of inflation is in fact similar in high- and low-income countries, casting doubt on the idea that economic development mitigates the impact of temperature shocks. None of the papers above studies jointly the response of output and inflation and, equally important, how monetary policy has responded to these shocks.[6]

[6] Bennani and Farvaque (2024) look at the reaction of quarterly GDP and inflation in euro area countries to temperature anomalies since 1996 but, contrary to Ciccarelli, Kuik, and Hernández (2024) and our paper, they do not account for non linearities and differences between seasons, which prevents finding significant average results in the full panel of countries. Colombo and Ferrara (2024) look at the impact of different weather shocks - not only temperature - on the production of different sectors in Germany, France, and Italy since 1990. Contrary to our approach, they neither focus on summer shocks nor consider different thresholds.

Section I presents our dataset, and section II outlines our estimation strategy. Section III shows the effects of a high temperature shock on production, prices and the central bank interest rate for several periods and several panels of countries.

1 Data

To study the short-term impact of temperature shocks on the economy, we construct a monthly dataset including both economic variables and temperature information from 1920 to 2019.

Economic variables are the monthly production index, the price index and the interest rate of the central bank. They are obtained from the dataset of (Bazot, Monnet, and Morys, 2024) and sources are listed in Appendix B . This dataset covers 14 Europeans countries, with monthly data from 1920 to 2019. The interest rate is the leading policy rate of the central bank. We use year-on-year variations for industrial production and the consumer price index.

The temperature dataset comes from the Berkeley Earth project (Rohde and Hausfather, 2020). Their data are derived from 14 databases, covering 44,455 measurement sites worldwide. After processing and merging duplicates, as well as removing series that were overly short (less than one year) and sites with missing or uncertain data, Berkeley Earth has 36,866 measurement sites. In order to avoid the problems associated with data from meteorological stations (Auffhammer, Hsiang, Schlenker, and Sobel, 2013), the data processing used by the Berkeley Earth project involves the following steps, with the aim of moving from station-by-station measurements to a country-average temperature. First, a temperature is given at each point on the globe by interpolation from the temperature records, by the Kriging method relying on distance and covariance between stations to calculate intermediate values. Then a regional surface average (and not station average) temperature is constructed to identify outliers, that mean records not consistent with the regional field. An iterative process is used to detect these outliers and weight the stations in order to reduce their contribution to the local field.

In this paper, we are interested in temperature anomalies, i.e. the deviation of temperature in a given month for a given country from the long-term average temperature. Following common practice, the base period for this long-term average is from January 1950 until

December 1980.[7] The first signs of an increase in temperature due to global warming appear around 1980. So 1950-1980 appears to be the period with the most complete and most high-quality data to serve as a benchmark to calculate anomaly. The temperature anomaly for the country c at month m of year y is defined as the difference between the corresponding temperature and the mean of the temperature in c for m during the 31 years between 1950 and 1980, ie :

$$anom_{c,y,m} = T_{c,y,m} - \frac{1}{31} \sum_{a=1950}^{1980} T_{c,a,m}$$

where $T_{c,y,m}$ is the temperature for the country c at month m of year y. The results presented in this paper are robust to a different reference period.

2 Identification and modeling strategy

Our estimation focus on hot shocks occurring during the summer months (June, July, August, and September). Indeed, a high temperature shock in the winter - even if unusual - is unlikely to create a situation that disrupts production since the level of temperature that is reached is not unknown during other seasons. By contrast, a high temperature in the summer can create conditions to which the economy is not adapted nor adaptable.[8]

In order to study the short-term reaction of economic variables to an exogenous temperature shock, we estimate impulse response functions (IRFs) using local projections, following a now well-established empirical literature (Jordà (2005); Ramey (2016); Òscar Jordà (2023)). Unlike other models such as vector autoregressive models (VAR), this method has the advantage to not rely on a predefined model and to not constrain the shape of IRFs (Auerbach and Gorodnichenko (2012); Nakamura and Steinsson (2018)). They can produce equivalent results to VARs if the number of lags is sufficiently high in relation to the forecast horizon (Plagborg-Møller and Wolf, 2021). They are now commonly used in recent literature to estimate the impacts of fiscal policy shocks, monetary policy shocks or, like this article, climate shocks (Faccia, Parker, and Stracca (2021); Natoli (2024); Lucidi, Pisa, and Tancioni (2024); Cevik and Jalles (2023); Colombo and Ferrara (2024)).

[7] The 1950-1980 baseline is widely used in the literature to calculate temperature anomalies. Among others, it is the baseline chose by the NASA `https://earthobservatory.nasa.gov/world-of-change/global-temperatures` or the FAO United Nations `https://www.fao.org/faostat/en/#data/ET`.

[8] (Colacito, Hoffmann, and Phan, 2019; Faccia, Parker, and Stracca, 2021; Ciccarelli, Kuik, and Hernández, 2024; Lucidi, Pisa, and Tancioni, 2024; Kotz, Kuik, Lis, and Nickel, 2024) also focus on the economic impact of summer temperature shocks for the same reason.

The issue of non-linearity is crucial as far as temperature anomalies are concerned. The effect of a temperature anomaly materializes only if the anomaly exceeds a certain threshold. Therefore, we follow the recent empirical macroeconomics literature that has emphasized the importance of allowing for nonlinearities when estimating the effects of exogenous shocks on macroeconomic variables of interest (Auerbach and Gorodnichenko (2012); Gonçalves, Herrera, Kilian, and Pesavento (2024)). We use state-dependent impulse response functions where the effect of the temperature anomaly is allowed to vary above a certain threshold. More precisely, we follow Auerbach and Gorodnichenko (2012) by allowing the transition between two regimes to be smooth, i.e. driven by a transition function.

Let K be the dimension of the vector of macroeconomic aggregates of interest. M is the number of countries i, T is the time dimension, and H is the time horizon for which we want to measure the response of a shock. Let $y^k_{i,t+h}$ be the macroeconomic variable for which we measure the response to a temperature shock in horizon $0 \leq h \leq H$. Lastly, let Y_t denote the vector of all $y^k_{i,t}$ variables.

The impulse response to a temperature shock δ is measured as :

$$IR(y^k_{i,t+h}) = E_{i,t}(y^k_{i,t+h}|\delta = 1; Y_{i,t}, Y_{i,t-1}, ...) - E_{i,t}(y^k_{i,t+h}|\delta = 0; Y_{i,t}, Y_{i,t-1}, ...)$$

In the rest of the paper, we will focus on hot shocks. A hot shock - normalized to 1°C - is thus defined as when our series of temperature anomalies takes the value $\delta = 1$ during a summer month.

The local projections consist of measuring $IR(y^k_{i,t+h})$ based on a sequence of predictive fixed effects panel regressions of the variable of interest on an exogenous shock to horizon h:

$$y^k_{i,t+h} = \alpha_i + \Phi_h(L)Y_{t-1} + \beta_h \text{anom}_t + \epsilon_{h,it} \qquad \text{for } h = 0, 1, 2, ..., H$$

where $\Phi_h(L)$ is the polynomial set of lag operator (which is set at 3 in our empirical analysis), anom_t is the value of the temperature anomaly, α_i the country fixed effects, and $\epsilon_{h,it}$ the residual. We also add monthly fixed-effects in Y_t to control further for seasonality. The impulse response is the set of estimated $\hat{\beta}_h$ from $h = 0$ to $h = H$. We will look at the responses of three independent variables y: the interest rate of the central bank (in level), the inflation rate (measured as the year-on-year price change) and the growth rate of output (measured as well as the year-on-year change to minimize seasonal effects).

To account for nonlinearity, we identify two regimes : one "normal" regime and one "shock" regime. Following Auerbach and Gorodnichenko (2012), we use state probabilities with a logistic function :

$$F(z_t) = \frac{e^{-\gamma z_t}}{1 + e^{-\gamma z_t}}$$

$\gamma > 0$ is a state-switching parameter measuring the speed at which we move from one regime to one another (see figure 11 in the appendix to see how different values of γ affect $F(z_t)$). $\gamma > 0$ is first calibrated to 3 following (Adämmer, 2019) but section 3 .4 and the appendix A will discuss the robustness of our results depending on different values of γ . The transition function $F(z_t)$ makes it possible to take into account observations close to the threshold, and to obtain results that are less sensitive to the choice of a given threshold. The threshold is nevertheless fixed (it will be 1°C or 2°C) and not time-varying. We have $z_t = anom - \tau$ with $anom$ the temperature anomalies and τ a defined threshold, an increase in z_t above τ leads to a decrease in $F(z_t)$, so, low $F(z_t)$ values indicates periods of a hot temperature shock. For example, for z=1 (i.e. for an anomaly of one degree above the fixed threshold), there is a 95% probability to be in the "hot shock state" insofar as $\gamma = 3$.

The specification used to estimate the state-dependent impulse response is then given by :

$$\begin{aligned} y^k_{i,t+h} =& \alpha_i + (1 - F(z_t)\,(\Phi_{h,1}(L)Y_{t-1} + \beta_{h,1}\text{anom}_t) \\ &+ F(z_t)\,(\Phi_{h,2}(L)Y_{t-1} + \beta_{h,2}\text{anom}_t) + \epsilon_{h,it} \qquad \text{for } h = 0, 1, 2, ..., H \end{aligned}$$

$F(z_t)\hat{\beta}_{h,1}$ is the reported coefficient used to produce the impulse response function of economic variables to the hot temperature shock. τ is the the switching threshold in the logistic function. In the following analysis, we will explore results for 1°C and 2°C thresholds. For reasons discussed above, we restrict our analysis to shocks occurring only during the summer months (June, July, August and September), so $anom = 0$ in all other months. From an econometric point of view, it is better to account for non-linearity with a time-invariant threshold (see Gonçalves, Herrera, Kilian, and Pesavento (2024)) rather than to take the average temperature as a threshold (as in (Kotz, Kuik, Lis, and Nickel, 2024)) since the average temperature and the frequency and size of anomalies are correlated.

3 The effect of high temperature shocks

3 .1 Groups of countries and descriptive statistics

Our study focuses on 14 European countries for three main reasons. Firstly, unlike the United States or China, for example, these countries are small enough that temperature variations within the same country are limited over the course of a given month. It is therefore possible to work with national data and averages. Secondly, with the exception of the United States and Japan, these are the only countries for which we have been able to obtain consistent monthly data on prices and production since 1920. Thirdly, these countries are relatively homogeneous in terms of economic development and climatic conditions. This limits the number of non-linearities (apart from temperature thresholds) to be taken into account in the estimation model.

The 14 European countries may exhibit differences in their average temperatures as well as the frequency and the strength of high temperature anomalies. We first investigate the different weather conditions. The descriptive statistics (the average anomalies and their frequency, plus the correlations between countries) shown in figure 1 highlight different groups of countries. The first group consists of Western and Central European countries: Austria, Belgium, France, Germany, Netherlands, Switzerland. A 2nd group consists of Southern European countries, including Portugal, Spain and Italy. A third group is made up of England and Nordic countries (Denmark, Finland, Sweden, Norway). The first and second group differ in their average temperature but not so much in the size and frequency of temperature anomalies during summer, which is the focus of our analysis. By contrast, the third group (of Northern countries) shows lower average temperature and lower anomalies. The average anomaly in the third group, for the post-1980 period, does not exceed 0.65, whereas it is between 0.8 and 1.1 in the countries of the first two groups. The frequency of anomalies greater than 1°C is 1.36 on average in the third group since 1980, but close to 2 in all the other countries. A frequency of 2 means that the monthly temperature is 1°C above the reference average for 2 months of each year. Beside, in historical periods, the group of Northern economies often had negative average anomalies. Figure 18 in appendix 18 shows the frequency of temperature anomalies over the period 2000-2019. Only the countries in the first and second groups have a frequency of anomalies above 1° at least equal to 2 (i.e. occurring more than two months per year) and frequency of anomalies above 2° at least equal to 1 (i.e. occurring more than one month per year) over the recent period 2000-2019.

For this reason, we consider England and Nordic countries to be in a special position relative to the others: they are less affected by frequent high temperature anomalies. As one of the aims of our exercise is to discuss the future of macroeconomic fluctuations in a world of more frequent and higher temperature shocks, we exclude these countries from our baseline estimation sample. We will incorporate them in a second step, for the purpose of comparison, in section 3 .4.

Consequently, we focus first on a panel of 9 countries. Temperature shocks are highly correlated between the Western European countries, as shown in the bottom panel of figure 1. The shock may be a common one, amplified by the correlation between countries. Thus, even though this does not affect the interpretation of the results, we need to correct the standard errors for the correlation between countries using the procedure of Driscoll and Kraay (1998).

Average summer temperature (°C)	FIN	NOR	SWE	DEN	ENG	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
Période 1920-1936	12,1	8,4	11,7	14,8	13,7	15,6	16,0	15,5	14,1	14,6	17,2	20,3	20,8	20,4
Période 1950-1979	12,2	8,6	12,0	15,1	13,8	15,7	16,0	15,6	14,2	14,6	17,2	20,3	20,8	20,3
Période 1980-2019	12,7	9,1	12,5	15,7	14,4	16,5	16,9	16,5	15,2	15,6	18,2	21,4	21,9	21,3

Average summer anomaly (°C)	FIN	NOR	SWE	DEN	ENG	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
Période 1920-1936	-0,08	-0,15	-0,24	-0,25	-0,09	-0,04	-0,01	-0,09	0,01	0,02	0,08	0,10	0,11	0,03
Période 1950-1979	-0,02	-0,02	-0,02	0,01	0,01	0,02	0,03	0,04	0,06	0,06	0,05	0,07	0,02	0,00
Période 1980-2019	0,53	0,55	0,54	0,60	0,65	0,81	0,87	0,88	1,07	1,08	1,03	1,13	1,13	1,01

Frequency of summer anomalies >1°C per year	FIN	NOR	SWE	DEN	ENG	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
Period 1920-1936	1,06	0,71	0,82	0,65	0,65	0,76	0,76	0,76	0,76	1,00	1,06	0,71	0,82	0,53
Period 1950-1979	0,93	0,53	0,93	0,80	0,53	0,73	0,80	0,80	0,80	0,87	0,70	0,67	0,60	0,60
Period 1980-2019	1,45	1,28	1,43	1,40	1,25	1,63	1,83	1,68	2,00	2,18	2,03	2,20	2,25	1,98

Frequency of summer anomalies >2°C per year	FIN	NOR	SWE	DEN	ENG	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
Period 1920-1936	0,29	0,18	0,24	0,12	0,06	0,18	0,24	0,24	0,29	0,41	0,29	0,24	0,24	0,18
Period 1950-1979	0,37	0,10	0,17	0,17	0,13	0,20	0,27	0,17	0,17	0,17	0,13	0,20	0,07	0,10
Period 1980-2019	0,78	0,33	0,45	0,45	0,35	0,70	0,80	0,83	1,03	1,08	0,88	0,90	0,68	0,78

	FIN	NOR	SWE	ENG	DEN	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
FIN	1	0,85	0,91	0,37	0,66	0,43	0,35	0,43	0,33	0,25	0,22	0,19	0,02	0,01
NOR	0,85	1	0,95	0,56	0,75	0,52	0,43	0,48	0,32	0,28	0,27	0,17	0,03	0,02
SWE	0,91	0,95	1	0,57	0,82	0,58	0,49	0,55	0,40	0,34	0,31	0,24	0,06	0,05
ENG	0,37	0,56	0,57	1	0,78	0,85	0,83	0,75	0,57	0,65	0,72	0,40	0,43	0,41
DEN	0,66	0,75	0,82	0,78	1	0,87	0,78	0,85	0,67	0,60	0,57	0,43	0,22	0,17
NLD	0,43	0,52	0,58	0,85	0,87	1	0,98	0,96	0,82	0,82	0,83	0,61	0,44	0,34
BEL	0,35	0,43	0,49	0,83	0,78	0,98	1	0,96	0,85	0,89	0,91	0,68	0,53	0,42
DEU	0,43	0,48	0,55	0,75	0,85	0,96	0,96	1	0,92	0,88	0,84	0,72	0,44	0,32
AUT	0,33	0,32	0,40	0,57	0,67	0,82	0,85	0,92	1	0,92	0,82	0,88	0,47	0,32
CHE	0,25	0,28	0,34	0,65	0,60	0,82	0,89	0,88	0,92	1	0,95	0,89	0,66	0,50
FRA	0,22	0,27	0,31	0,72	0,57	0,83	0,91	0,84	0,82	0,95	1	0,80	0,75	0,61
ITA	0,19	0,17	0,24	0,40	0,43	0,61	0,68	0,72	0,88	0,89	0,80	1	0,61	0,42
ESP	0,02	0,03	0,06	0,43	0,22	0,44	0,53	0,44	0,47	0,66	0,75	0,61	1	0,93
PRT	0,01	0,02	0,05	0,41	0,17	0,34	0,42	0,32	0,32	0,50	0,61	0,42	0,93	1

Figure 1: Averages, frequency and correlations of high temperature anomalies during the summer

Note: a frequency of 1 means that summer temperatures exceed the threshold (1 or 2°C) during 1 month per year on average.

Figure 2 shows the evolution of the anomalies during summer of the nine included countries since 1920. It confirms the information from Figure 1 that large anomalies (above 2°C) were more frequent before 1950 than between 1950 and 1980. It also shows that anomalies have reached an unprecedentedly high frequency in the recent decades.

3 .2 Average effect of temperature shocks

Given the rarity of anomalies above 2°C in the past, we first focus on results derived from a 1°C threshold. Figure 3 summarizes the average panel results for our benchmark panel of 9

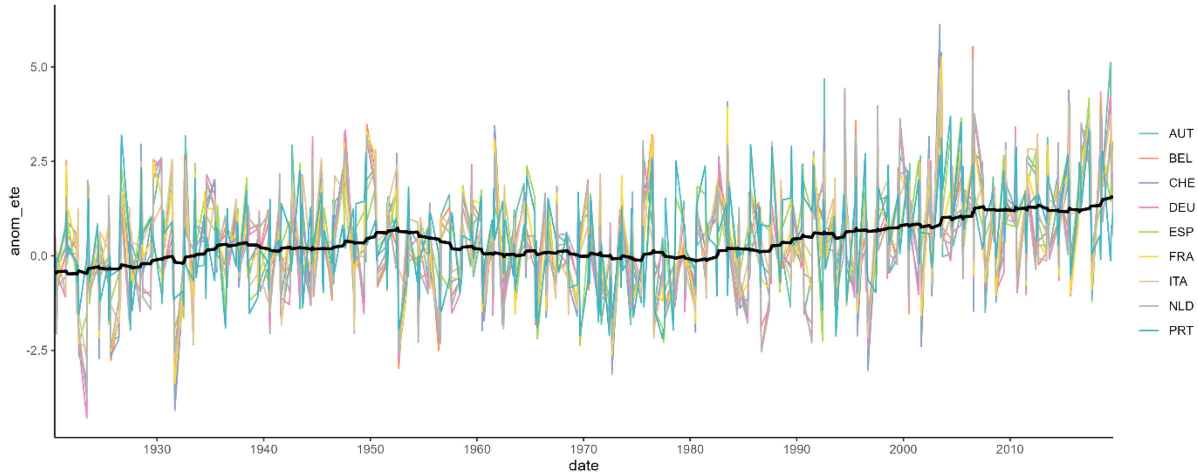

Figure 2: High temperature anomalies during the summer, 1920-2019. (Deviation from average temperature over 1950-1980). Main sample of 9 countries.

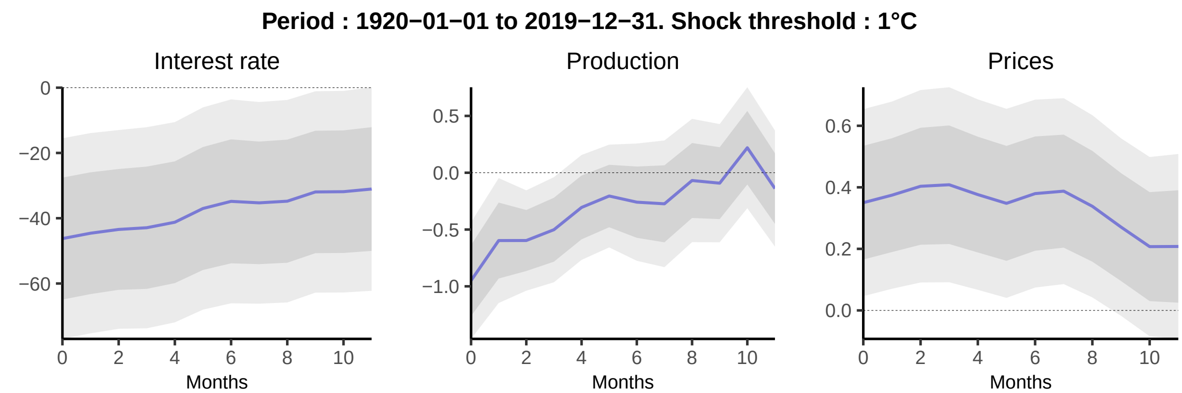

Figure 3: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries), 1920-2019.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

Southern/Western European countries.[9] We simulate the effect of a moderate hot temper-

[9]We first exclude observations between 1937 and 1949 because monthly data just before, during and after the Second World War suffer from quality problems, in particular price data affected by price controls, and are marked by abnormal volatility due to the wartime situation. In addition, central bank interest rates generally remained unchanged during these years. Yet, as shown in figure 10, results are very similar when we include data available between 1937 and 1949. Please note that there is no production index for Portugal, Spain and Italy before 1936. The available series of monthly production for these countries in the interwar period

ature shock (above 1°C) during the summer for the entire period 1920-2019. The shock is normalized to 1°C (above the threshold). The effects on output and prices are typical of a supply shock. The year over-year variation in the industrial production declines by around 0.9 pp and goes back to normal in 4 months. In other words, if the year-on-year output growth rate is, say, 2% in normal time, it immediately switches to 1.1% after the shock and progressively comes back to 2% in four months. There is no rebound effect with positive growth. This means that the effect on growth - even if temporary - causes a permanent loss of output. The year-on-year inflation rate increases by 0.4 pp, and the effect is more long-lasting. This means that, if the annual inflation rate is, say, 2% in normal time it immediately switches to 2.4% after the shock and progressively comes back to 2% in nine months. Interestingly, this temperature shock is also associated with a fall of the central bank interest rate by 40 basis points which comes back to zero within a year.

The effects of the high temperature shock (above a 1° threshold) on macroeconomic variables are thus significant and large. They are also immediate. These effects are typical of a supply shock, to which the central bank responds by lowering the interest rate, thus prioritizing production. The reason for this priority might be that the production response is slightly larger immediately after the shock. The response of the central bank interest rate is also consistent with the more persistent impact on the inflation rate: the decrease in the interest rate brings the impact of the shock on production growth back to zero after 3 months but it maintains inflationary pressures for a longer period, about 8 months.

It is worth comparing our results with standard estimates of the impact of monetary policy shocks. The state-of-the art recent studies on monetary policy shock on the United States and the Euro area (Jarociński and Karadi (2020); Miranda-Agrippino and Ricco (2021); Bauer and Swanson (2023)) find an immediate negative response of monthly industrial production and consumer prices to a 100 basis points (bp) rise in the central bank interest rate. The response of the growth of industrial production is usually around 1.2 pp while the response of prices is lower, around 0.3 pp. Thus, when compared to conventional effects of monetary policy shocks, our estimates show a strong impact that cannot be neglected by central banks. Without building a full-fledged counterfactual, this comparison also helps assessing to what extent the response of the interest rate might influence the responses of production and inflation to temperature shocks. In particular, a back-to-the envelope calculation means

concern only one or a subset of goods which are not representative of total industrial and manufacturing output. The figures 8 and 9 make clear that the impact of the shocks on the inflation rate is in fact stronger over the full 1920-2019 sample when we exclude these three countries.

that, without the 40bp decrease in interest rate observed in Figure 3, the inflation rate could have increased by 0.25pp instead of 0.4pp. So, the rise in the interest rate may explain only a limited part of the rise in inflation.

3 .3 Have the effects been similar in recent decades?

The effect of hot temperature shocks might be lower today than in the past for various reasons, in particular technological improvements (e.g. air conditioning) and a decrease in the share of the agricultural sector in total activity and food in total consumption. The latter in particular might tame the effects on consumer prices which are less dependent on agricultural good, while industrial production is only affected indirectly by the lower importance of the agricultural sector.

Figure 4 show similar responses as in Figure 3 but for shorter samples, starting respectively in 1950, 1990 and 2000. Estimations on shorter samples bear the risk of lower significance since the shocks we are interesting in occur rarely - and, by construction, only during 4 months a year. But significance only disappears completely in the shortest sample (except for the interest rate) starting in 2000. The most striking result in this Figure is the much lower effect of the shock on the inflation rate in the more recent samples. The effect at the impact is just equal to 0.1pp (instead of 0.4pp over the full 1920-2019 sample) when the sample starts in 1990. It is below 0.1pp and non-significant in the 2000-2019 sample. When interpreting these figures, it should also be noted that average inflation has decreased over time, so that a 1pp cumulative shock today is larger relative to the average inflation than in the 1920 and the 1950-1980s. Lastly, the declining effect we document can be due to the adaptation of advanced economies to climate change.

The threshold above which the shock affects the responses of production and inflation may have increased over the course of history. Thus, it can be instructive to look at the results with a threshold of 2°C. Figure 5 highlights again the importance of considering non-linearities. Note that we now consider summer temperature anomalies over a 2°C threshold but the size of the shock in our local projection is still set to 1°. Our results reveal that a 1° shock above a 2° threshold has quite similar effects on interest rates and production than a 1° shock above a 1° threshold. But the effect is remarkably stronger on the inflation rate. This holds true over the 1920-2019 sample (0.75pp instead of 0.4pp in Figure 3) as well as for recent periods. The response of the inflation rate is significant and equal to 0.2pp at impact in the 2000-2019 sample.

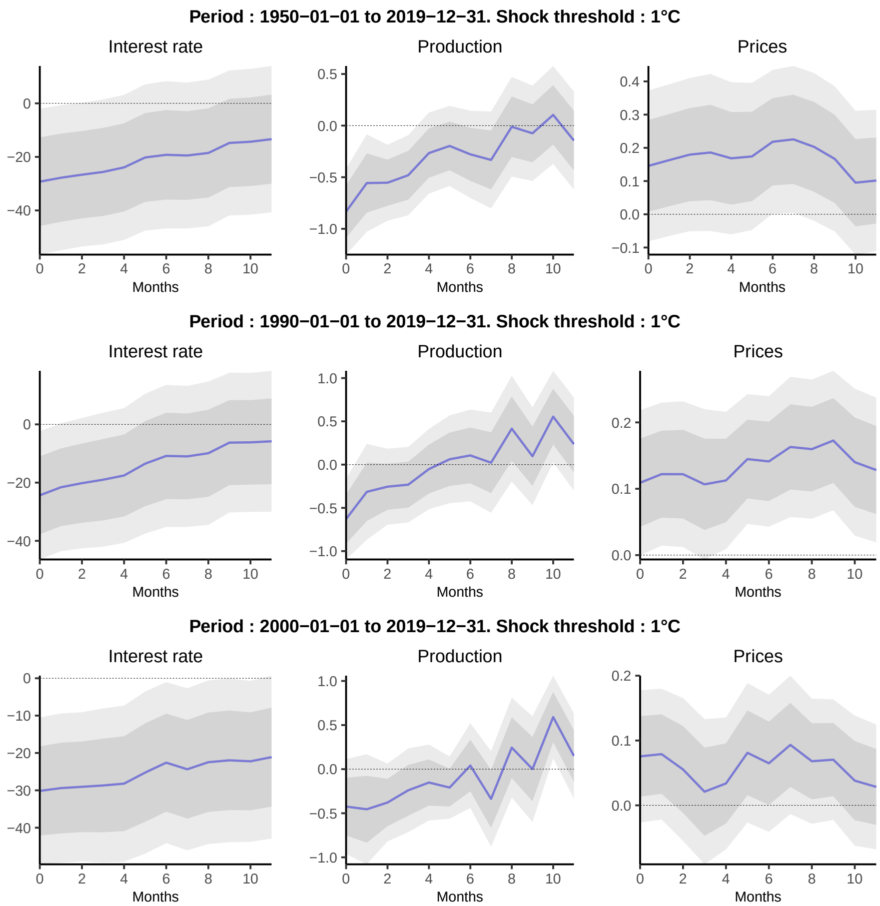

Figure 4: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 3 different periods.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

The average response of the inflation rate to summer hot shocks is thus lower today and it is visible only for large anomalies, that is those above 2°C. Yet, as Figure 1 shows, the frequency and the average size of the shocks have increased over time. So the shocks have a lower effect on inflation but are more frequent. According to Figure 1, no country has had a frequency of above-average summer temperatures for more than one month over the period 1950-1979 (i.e. the frequency is always less than 1 over this period). On the contrary, over the period 1980-2019, all the countries in our sample have a frequency greater than 1 (i.e. at least one summer month has had 1°C above-average temperatures). And 6 out of 14 countries have a frequency greater than 2. As far as the frequency of 2°C anomalies is concerned, we can

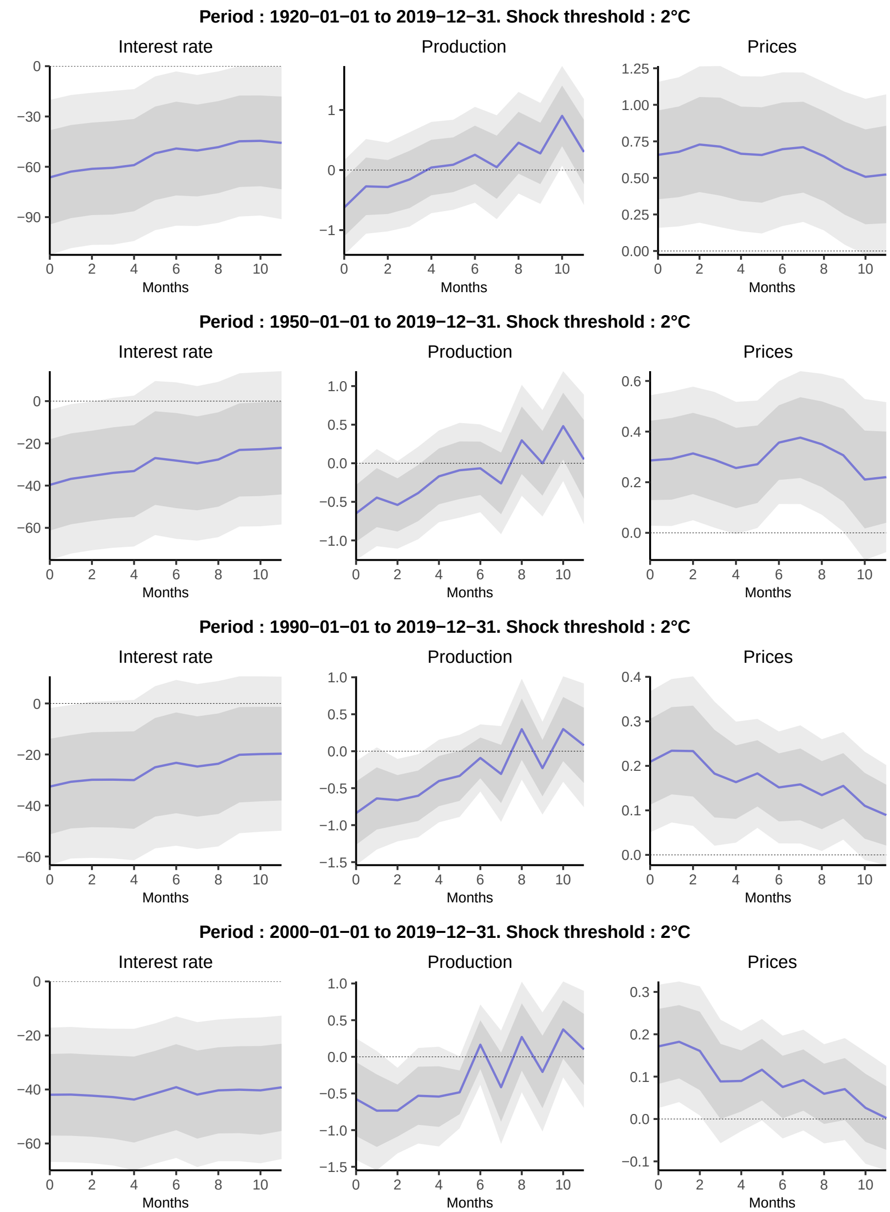

Figure 5: Effect of a hot temperature summer shock (above 2°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

see that only one country has a frequency greater than 0.2 over the period 1950-1979, which means that a month with a temperature 2°C above average has not occurred more than once every five years. In contrast, over the period 1980-2019, the frequency is close to 1 for several countries, meaning that a month with a temperature 2°C above average now occurs almost once a year. Figure 18 in appendix 18 shows the frequency of temperature anomalies over the period 2000-2019 and reveals that, in our reference sample of 9 countries, the frequency of anomalies above 2° is greater than 1 over this recent period (i.e. occurring more than one month per year).

3 .4 Robustness checks

Up to now, we have excluded England and the Nordic countries because the average value and the frequency of the summer hot temperature anomalies are generally far lower there than in the other European countries in our sample. Our conjecture is that including these countries in the sample would add noise to the estimations and drive potential effects down because they increase the number of summer fluctuations not caused by temperature shocks as well as the number of small anomalies that are just above the threshold and less likely to have an impact. Figure 6 verifies this conjecture (with a shock above a 1°C threshold). As when we compared Figure 5 and Figure 3, the inflation rate is the only variable whose recent patterns and significance are strongly affected when including more small shocks (this time by adding countries with lower average anomalies). It confirms that, especially in the recent periods, an impact of hot temperature on the inflation rate is observed in samples that contain large anomalies only (e.g. above the 2°C threshold). Estimations on the panel including Northern economies with a shock defined above 2°C shows that the response of prices is closer to significance (Figure 7) but still less significant and lower than when these Northern economies were excluded from the sample. This confirms our conjecture that there is no effect of hot temperature shocks - or we don't have enough statistical power to measure such effects - in countries where hot temperature anomalies are rare and smaller on average.

The previous discussion might raise concerns that our main results were in fact driven by the Southern European countries in our sample, where the average summer temperature is higher (but the hot temperature anomalies are neither more frequent, nor larger, as seen on Figure 1. Figure 8 and figure 9 show that it is not the case. Results are remarkably similar when we exclude Portugal, Spain and Italy from our sample.

Lastly, we propose to test the importance of the speed at which the model switches from one regime to another (γ). So far, we have set $\gamma = 3$. Now we look at the results for different value of this parameter ($\gamma = [2, 5, 10000]$) with a 1°C and 2°C threshold. Figures 12, 13, 14,

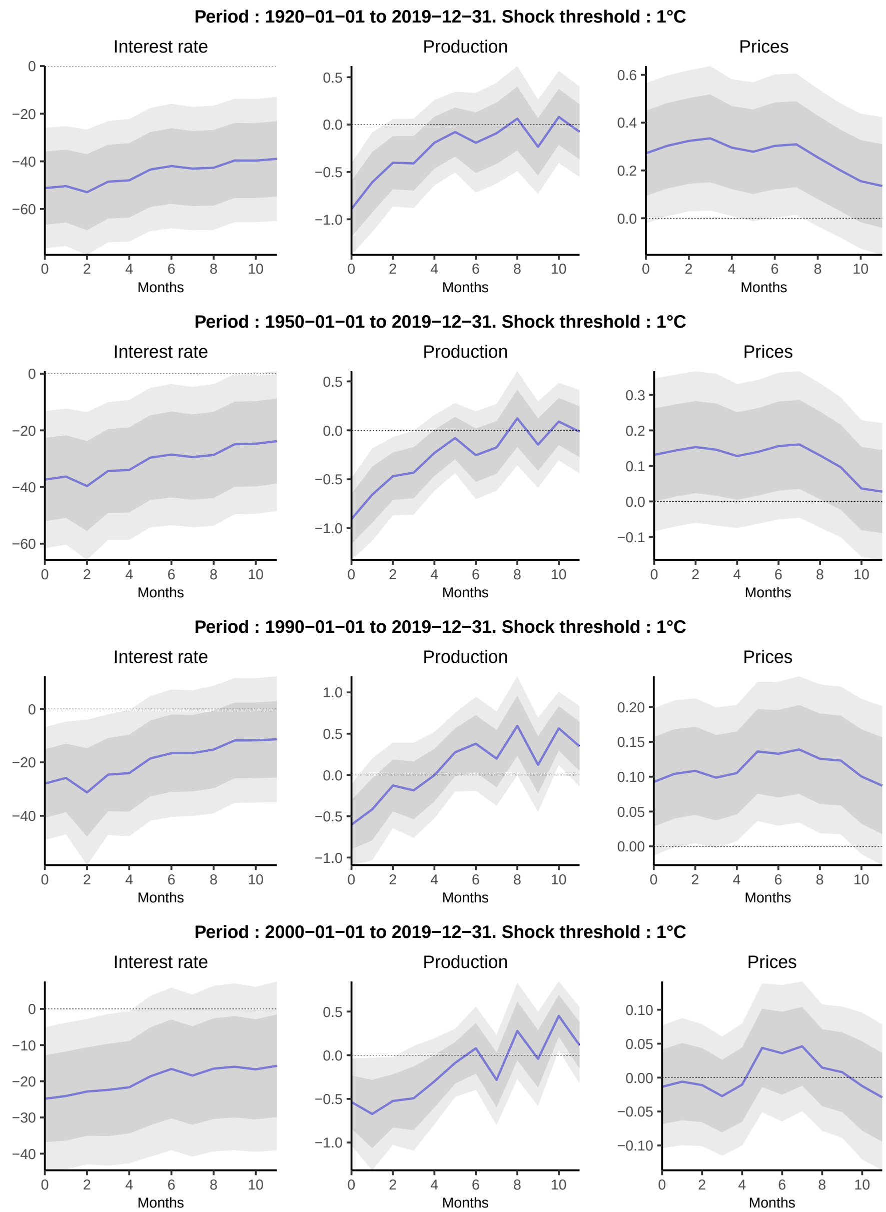

Figure 6: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (14 countries, including England and Nordic countries). 4 different periods.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

15, 16 and 17 in the appendix show that our results are very similar to the ones shown so far. Yet, the significance of the point estimates is slightly higher with $\gamma < 3$ and slightly

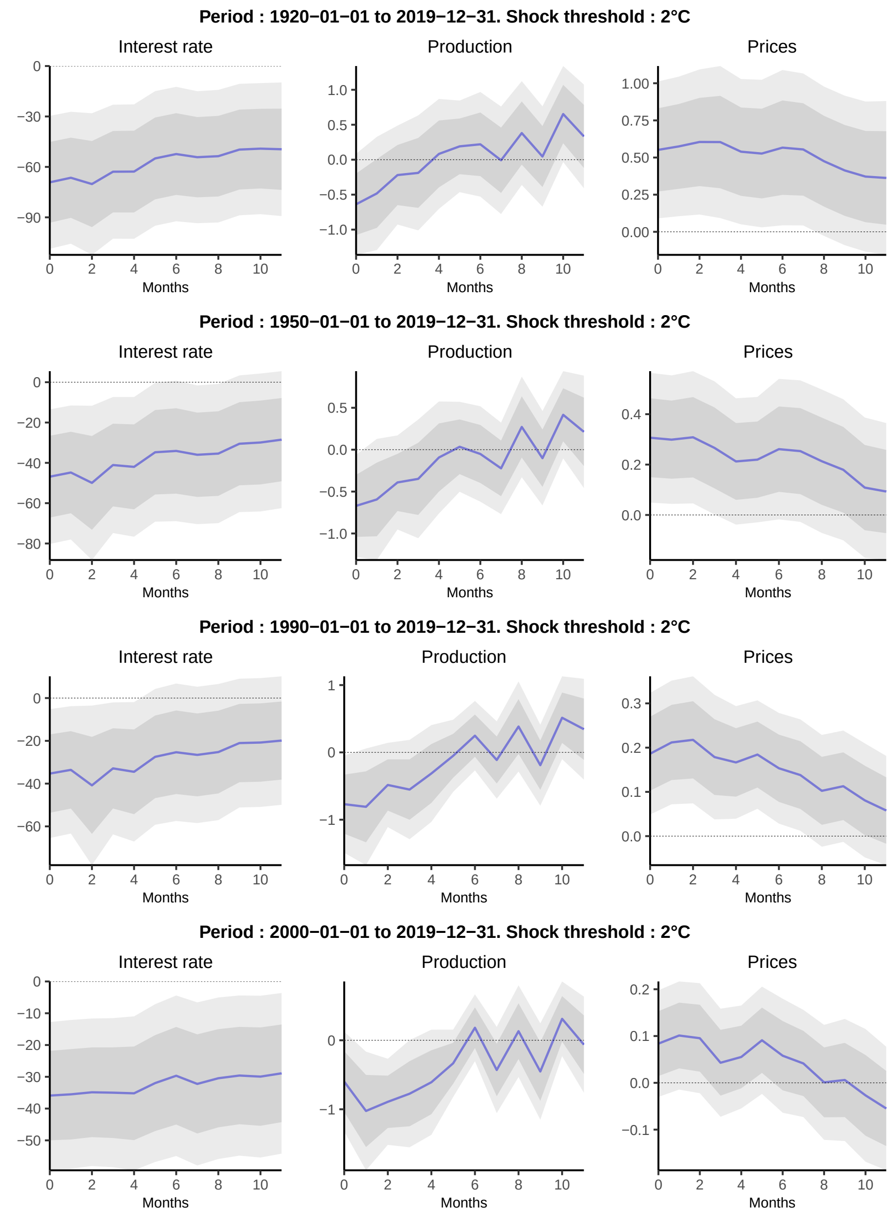

Figure 7: Effect of a hot temperature summer shock (above 2°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (14 countries, including England and Nordic countries). 4 different periods.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

lower with $\gamma > 3$. As shown on figure 11, a lower value of γ means that we include more observations around the threshold. On the contrary, a very large γ (such as $\gamma = 10000$) is

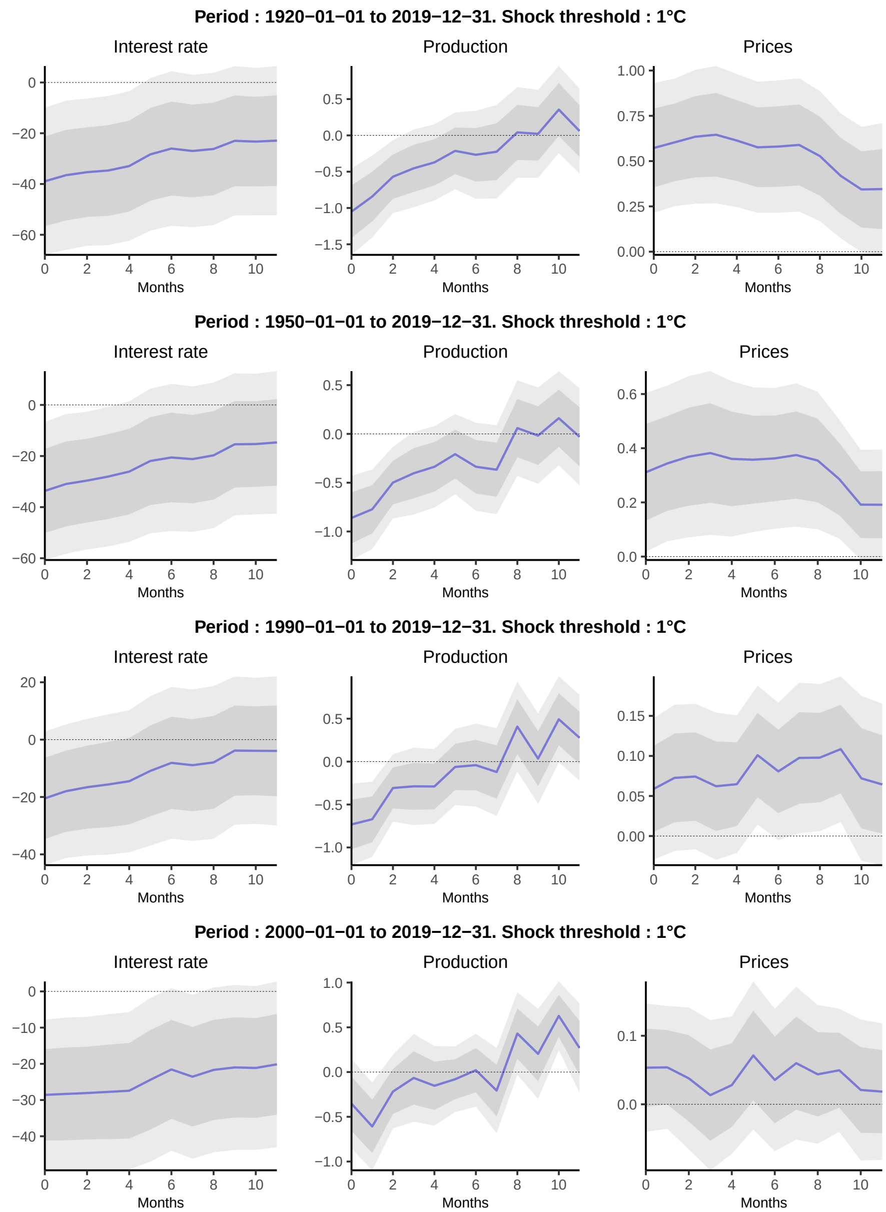

Figure 8: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Restricted sample of 6 countries: Austria, Belgium, France, Germany, Netherlands, Switzerland. 4 different periods.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

equivalent to an abrupt transition at the threshold, without including observations around it. A greater γ means that there is a smaller number of observations in the "shock" state and

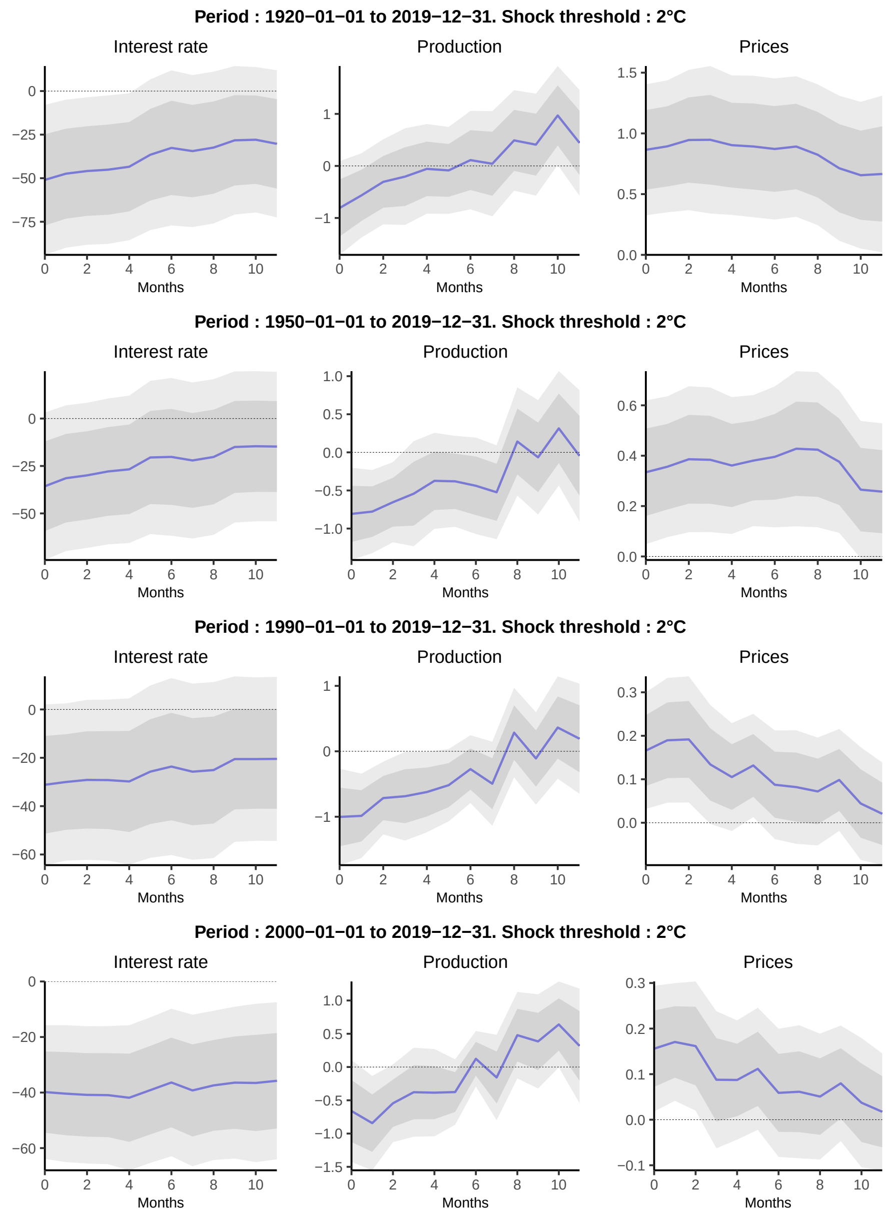

Figure 9: Effect of a hot temperature summer shock (above 2°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Restricted sample of 6 countries: Austria, Belgium, France, Germany, Netherlands, Switzerland. 4 different periods.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

our estimations are less precise. The results with $\gamma = 10000$ (i.e. no smooth transition) thus confirms that considering a smooth transition threshold *à la* Auerbach and Gorodnichenko

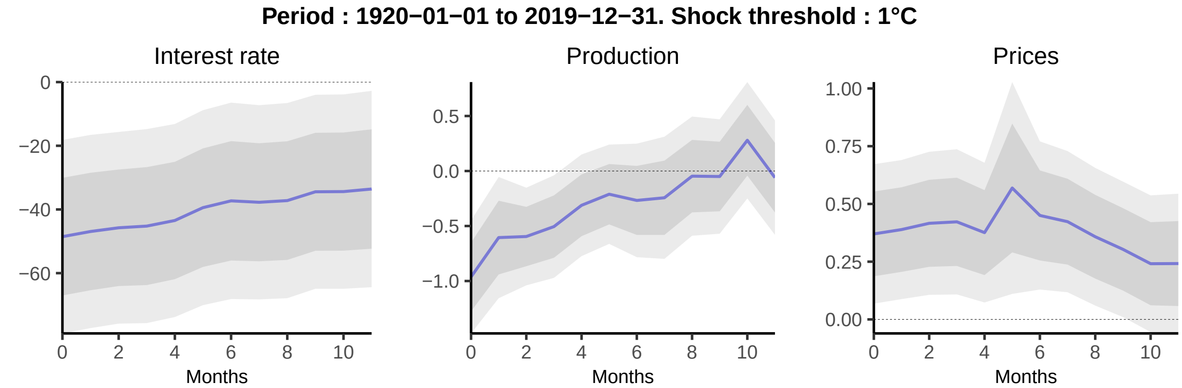

Figure 10: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries), 1920-2019, including 1937-1949.

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

(2012) is an appropriate method to increase the number of "anomalies" in the model and thus the precision of the estimates.

A final robustness check is simply to assess whether our results on the full sample 1920-2019 might be influenced by the exclusion of the period 1937-1949. We excluded those years due to doubts about the reliability of output and (especially) price data during this period around World War II. In figure 10, we simply reproduce our reference figure 3 (with the main sample of 9 countries and a threshold of 1°) while including the years 1937-1949. We see no major difference between the two sets of results. The only difference is that the response of the inflation rate is slightly higher after five months (reaching 0.5pp, instead of 0.4pp) when we include the years 1937-1949.

4 Conclusion

Even if far-reaching measures were taken today to combat climate change, studies show that the average temperature will rise in the coming decades, as will the frequency of extreme hot weather (e.g. Domeisen, Eltahir, Fischer, Knutti, Perkins-Kirkpatrick, Schär, Seneviratne, Weisheimer, and Wernli (2023). This article looks at the impact of such hot temperature anomalies in a centennial perspective. Measuring their impact is essential to know how macroeconomic policies should respond. Compared with the existing literature, our main methodological contribution is to use a new approach to take account of the non-linearity of shocks, to study jointly the responses of output growth, inflation and monetary policy, as well as to work with long, monthly data stretching back to 1920 for 14 European countries. This long panel allows us not only to increase the number of observations and shocks (thereby increasing the precision of our estimates) but also to compare the recent period with historical averages.

We emphasize three main conclusions. First, hot-temperature shocks are supply shocks: inflation rises and production falls. They therefore imply a new trade-off for macroeconomic policies, as it is more difficult to respond to supply shocks than demand shocks with a single instrument. Consequently, central banks, whose interest rate have repeatedly responded to the effects of hot temperature shocks in the past, will not be able to side-step the issue of climate change in future.

Second, the impact of a hot summer temperature shock is lower in recent decades than in the past, in particular the impact on consumer prices. Furthermore, anomalies that fall below a 2°C threshold are found to no longer have impacts in the last twenty years, on average. Given our methodology, we can only speculate on the precise reasons for this. Structural changes in the economy over time might be one reason. E.g., moving from a large agricultural sector - which by design is highly weather-dependent - to a service sector economy modelled around office work a century later might reduce the impact of individual shocks. Yet it is also possible that genuine adaptation, technological and otherwise, has helped reduce the shocks over time. There is a glimmer of hope in this particular finding.

Third, any euphoria stemming from our second conclusion needs to be put into proper perspective. While the effect of a single shock on consumer prices is weaker than in the past, we do not reach this conclusion for the effect on production. Most important, the effect on consumer prices is still visible for large temperature shocks (2°C above average) and the frequency of these shocks have increased. In our sample of reference countries, a monthly temperature anomaly greater than 2°C occurred one month a year on average over the period 2000-2019. This frequency has increased by a factor of 7 compared with 1950-1979, and by a factor of 3 compared with 1980-1999 (figure 18). In this way, the diminishing effect of a single shock is counterbalanced by an increase in the frequency of shocks. Our findings thus clearly stress that hot temperature shocks continue to create a major trade-off for central banks.

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ΩÒscar Jordà

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A Appendix: Robustness to different values of γ

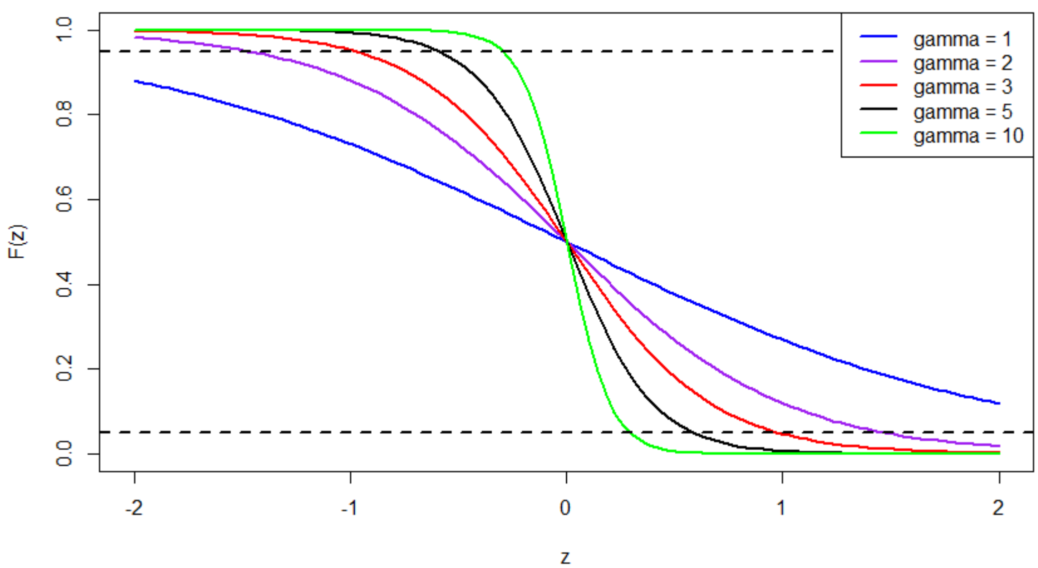

Figure 11: Transition function $F(z_t)$ according to different values of γ.

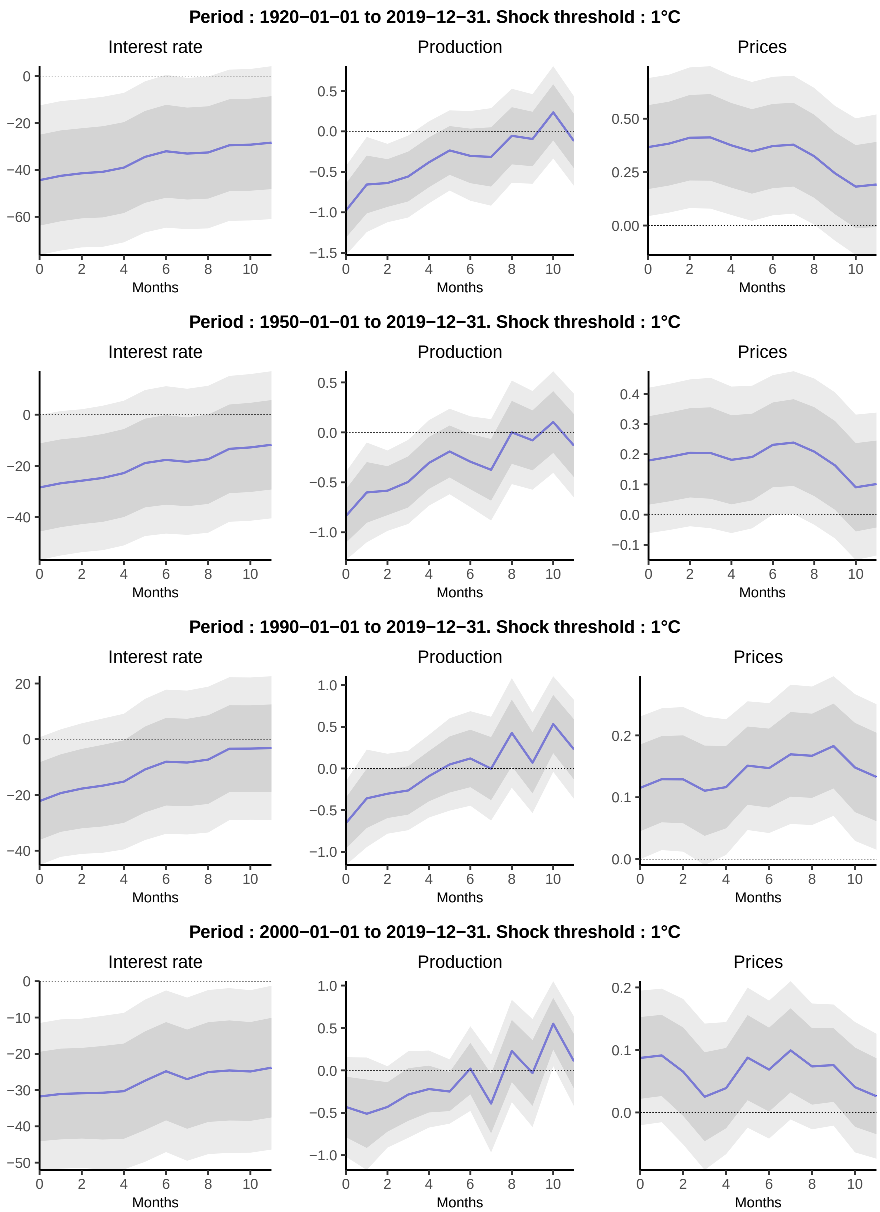

Figure 12: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods. $\gamma = 2$

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

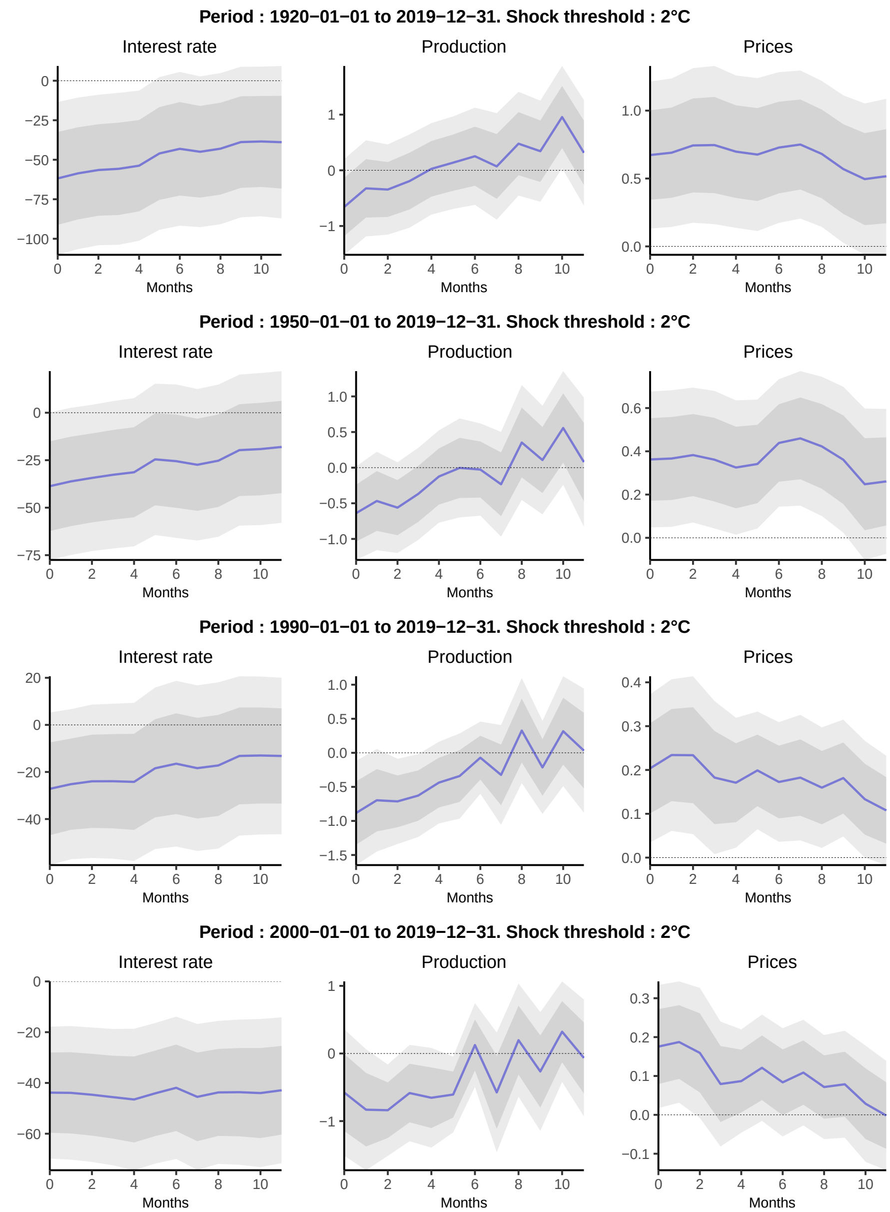

Figure 13: Effect of a hot temperature summer shock (above 2°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods. $\gamma = 2$

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

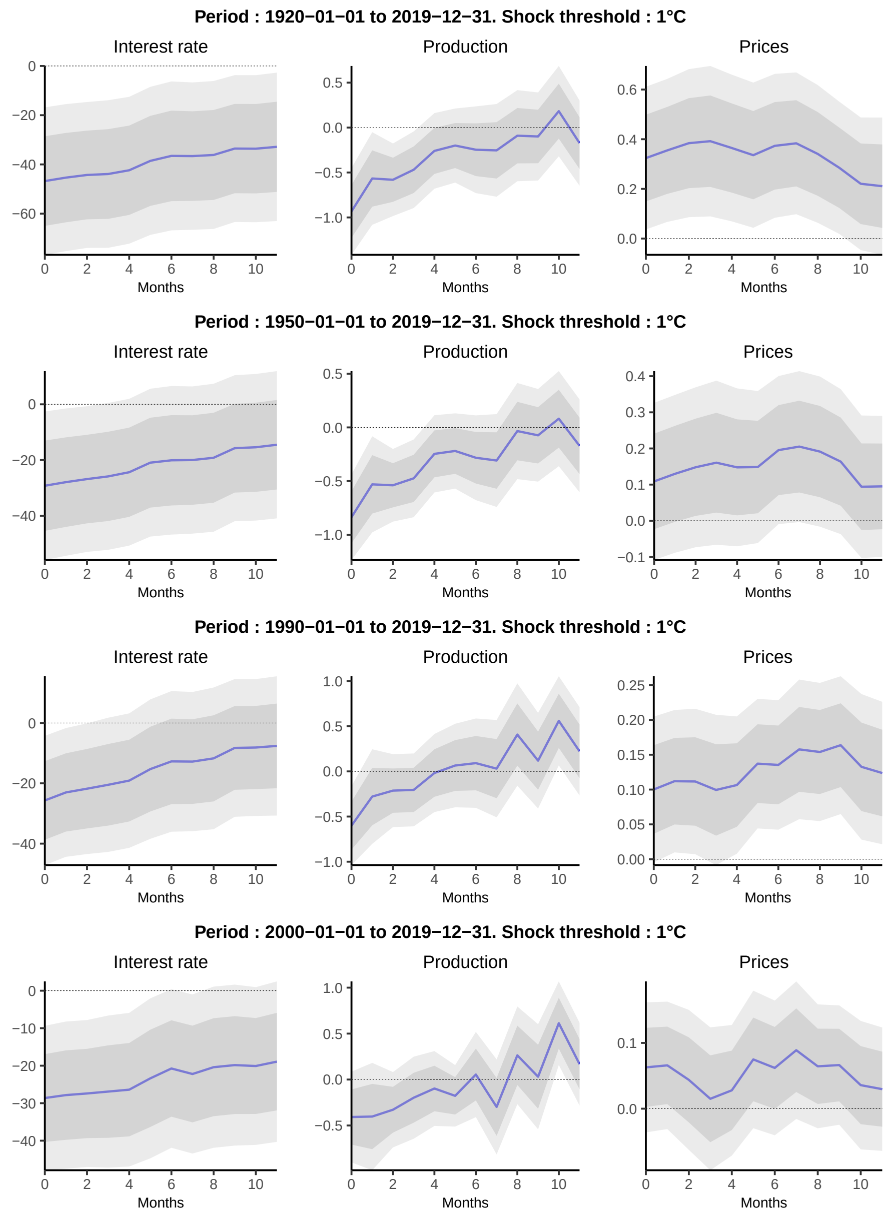

Figure 14: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods. $\gamma = 5$

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

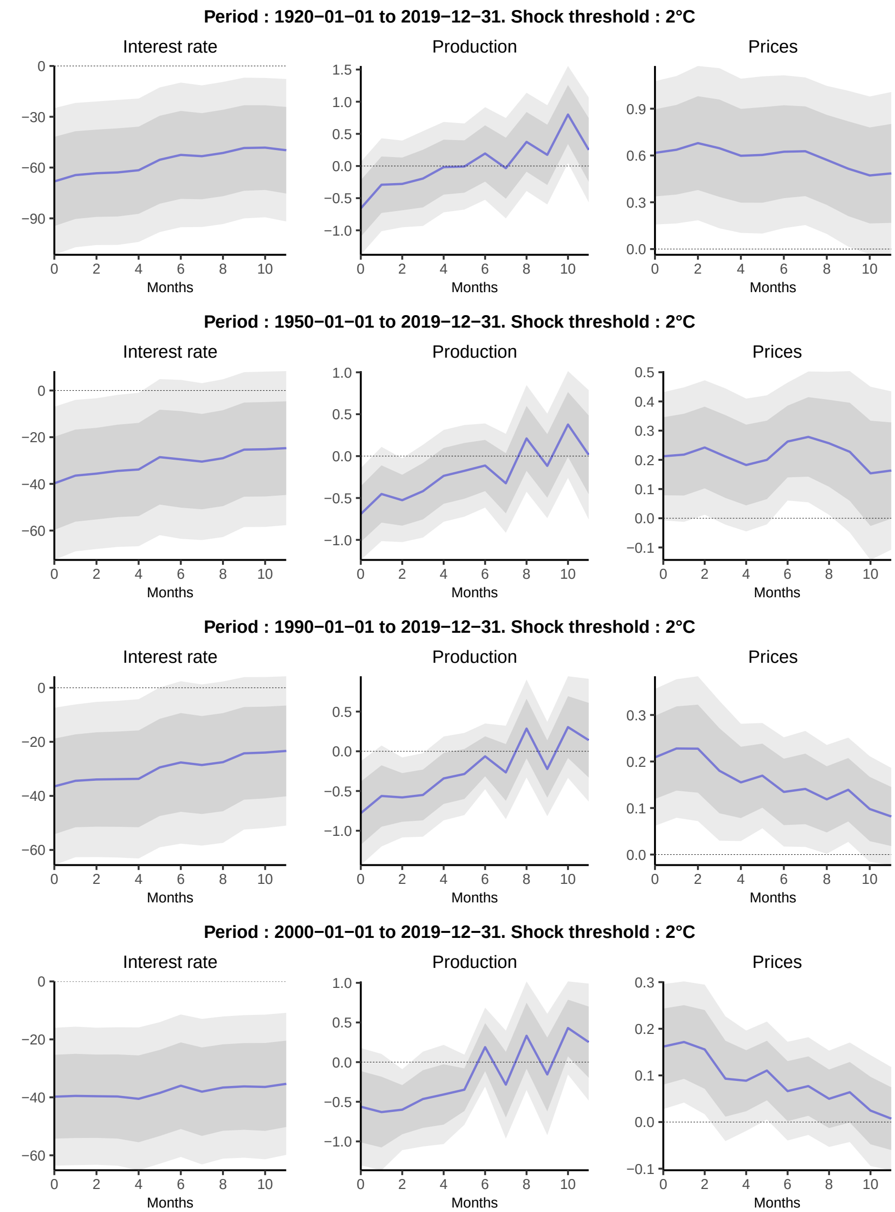

Figure 15: Effect of a hot temperature summer shock (above 2°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods. $\gamma = 5$

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

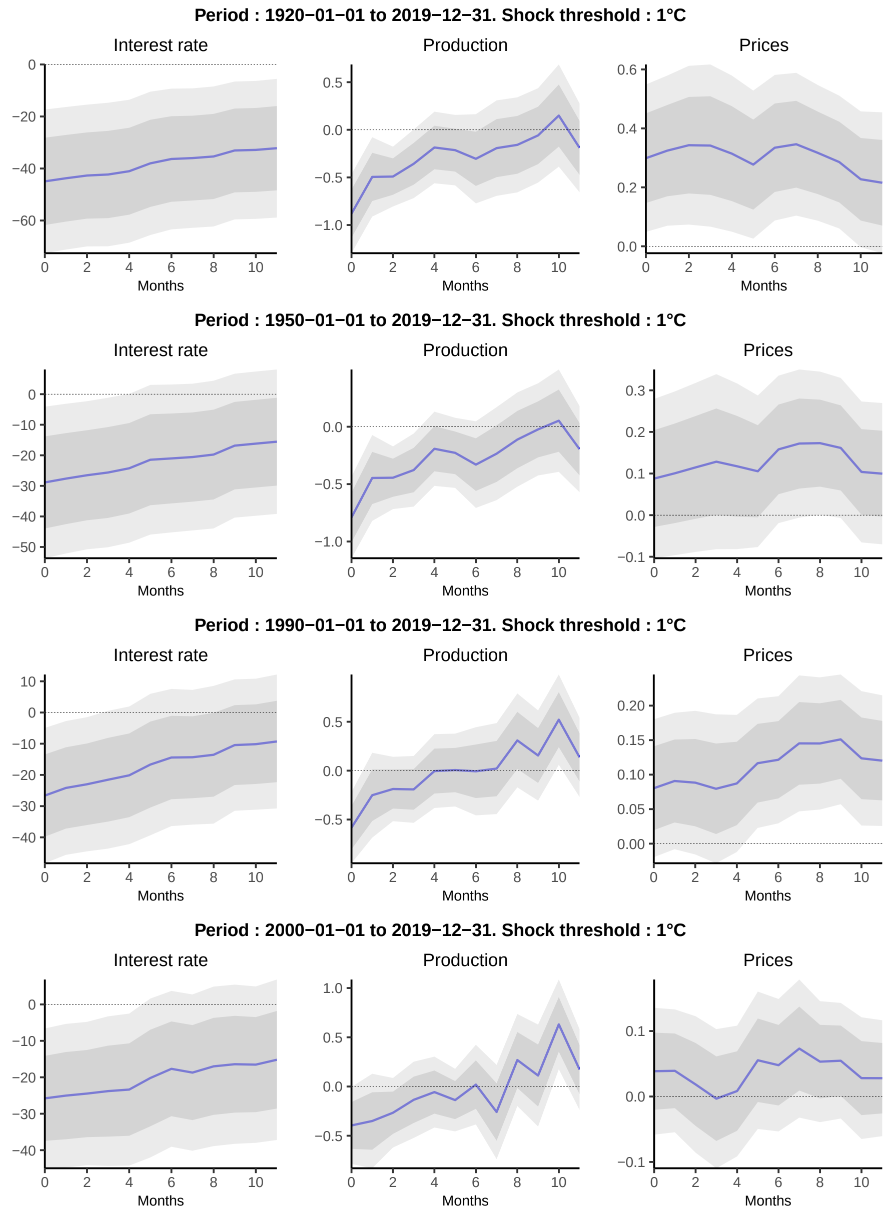

Figure 16: Effect of a hot temperature summer shock (above 1°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods. $\gamma = 10000$

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

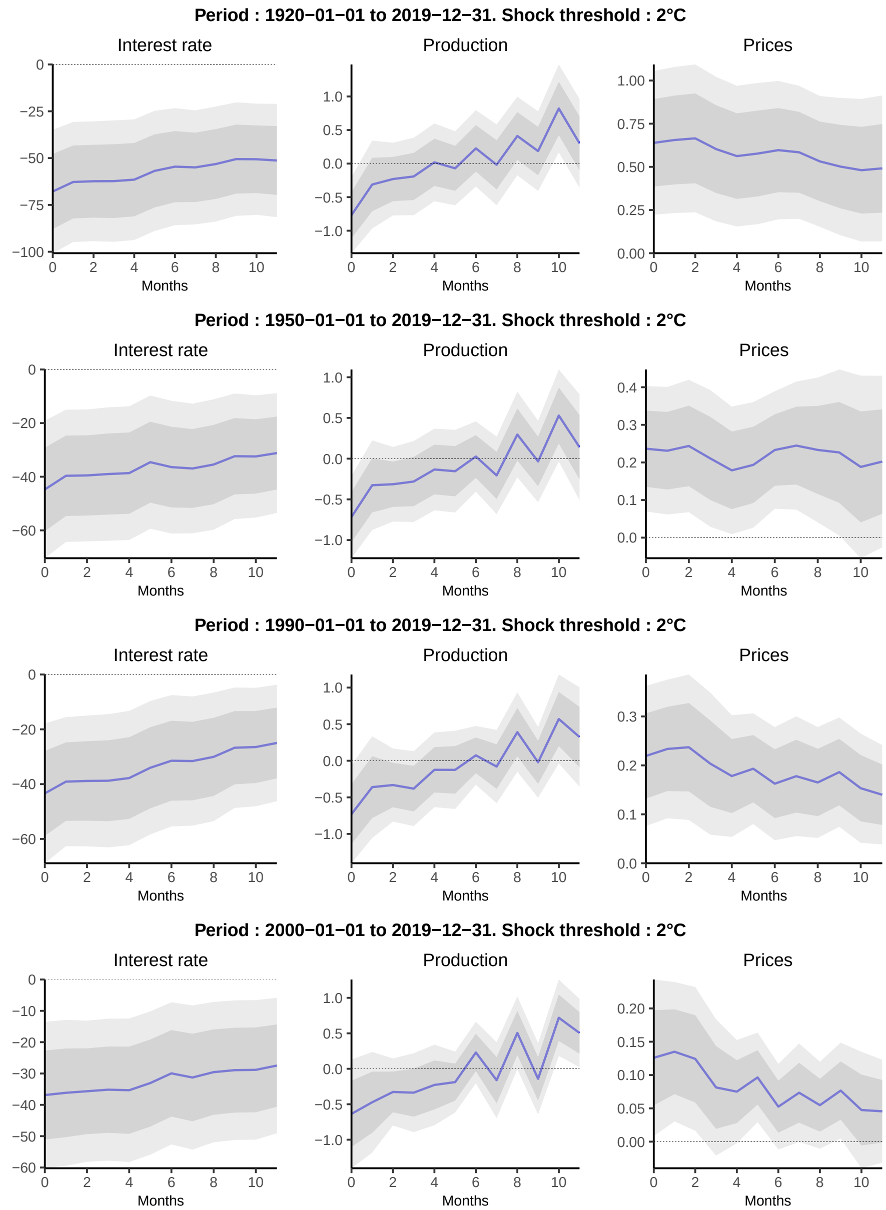

Figure 17: Effect of a hot temperature summer shock (above 2°C threshold) on the central bank interest rate, the growth of production and the inflation rate. Main sample (9 countries). 4 different periods. $\gamma = 10000$

Note: Responses to a 1° increase. The responses of the growth rates of production and prices are displayed in percentage points (pp). The response of the interest rate is in basis points (bp). Error bands correspond to the 68% and 90% confidence intervals and are calculated on the basis of Driscoll-Kraay standard errors.

B Appendix: frequency of temperature anomalies (alternative subsamples)

Frequency of anomalies above 2°C	FIN	NOR	SWE	DEN	ENG	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
Period 1920-1936	0,29	0,18	0,24	0,12	0,06	0,18	0,24	0,24	0,29	0,41	0,29	0,24	0,24	0,18
Period 1950-1979	0,37	0,10	0,17	0,17	0,13	0,20	0,27	0,17	0,17	0,17	0,13	0,20	0,07	0,10
Period 1980-1999	0,50	0,15	0,25	0,30	0,25	0,40	0,45	0,45	0,40	0,55	0,55	0,45	0,25	0,50
Period 2000-2019	1,05	0,50	0,65	0,60	0,45	1,00	1,15	1,20	1,65	1,60	1,20	1,35	1,10	1,05

Frequency of anomalies above 1°C	FIN	NOR	SWE	DEN	ENG	NLD	BEL	DEU	AUT	CHE	FRA	ITA	ESP	PRT
Period 1920-1936	1,06	0,71	0,82	0,65	0,65	0,76	0,76	0,76	0,76	1,00	1,06	0,71	0,82	0,53
Period 1950-1979	0,93	0,53	0,93	0,80	0,53	0,73	0,80	0,80	0,80	0,87	0,70	0,67	0,60	0,60
Period 1980-1999	1,05	0,75	0,85	0,90	0,85	1,10	1,40	1,05	1,30	1,75	1,50	1,55	1,85	1,70
Period 2000-2019	1,85	1,80	2,00	1,90	1,65	2,15	2,25	2,30	2,70	2,60	2,55	2,85	2,65	2,25

Figure 18: Frequency of high temperature anomalies during the summer

Note: a frequency of 1 means that summer temperatures exceed the threshold (1 or 2°C) for 1 month a year on average.

Central bank interest rates are taken from central bank sources presented and used in Bazot, Monnet, and Morys (2024).[10]

For the interwar period (1920-1930s), our main source is the monthly dataset compiled by Ellison, Lee, and O'Rourke (2024) and mainly based on the *International Abstract of Economic Statistics*, published in The Hague by Tinbergen (1934) and Derksen (1938) and the *Statistisches Handbuch Der Weltwirtschaft* (1936, 1937). We checked all series to ensure they were reliable enough for our purpose, especially that they included a sufficient number of goods and had patterns consistent with available annual data. When more comprehensive indices were built and published by economic historians, we used these sources on priority. For price indices, we often went back to the original series published by the League of Nations in its *Monthly Bulletin of Statistics* starting in 1919 (and made available online by the Center for Price Stability: `https://centerforfinancialstability.org/hfs/Data_notes.pdf`) as it allows us to choose between different price indices and select the one that most closely resembles a cost of living or consumer (retail) price index. This source is labeled LoN-CFS in the list below.

From the 1940s onward, we prioritized continuous historical series retrospectively published by historians or national statistics institutes when available, as well as series published on the website of the *International Financial Statistics (IFS)* by the International Monetary Fund (IMF): `https://data.imf.org/?sk=4c514d48-b6ba-49ed-8ab9-52b0c1a0179b`. In many cases, data are not available online before the mid-1950s or 1960s, so we used historical monthly printed volumes of the *International Financial Statistics (IMF)* published from 1948 onward. The series that were (and are still) published by the IMF were not produced by the IMF but by national statistical institutes or governments that, according to the 1944 Bretton Woods agreements, were committed to send them to the IMF (see Monnet and Puy (2021) for a presentation of this source). We built continuous series by rebasing the series obtained from different sources.

Austria

- **Production index:** 1919-1936 Ellison, Lee, and O'Rourke (2024); 1947-1955 IFS (print); 1956-2022 IFS (online)

[10] Due to difficulties in identifying the main relevant policy rate of the central bank (among the many used during this period), we exclude interest rates of the Bank of Spain between 1974 and 1979.

- **Price index:** 1922-1938 retail prices, LoN-CFS; 1946-1956 IFS (print); 1957-2022 IFS (online)

Belgium

- **Production index:** 1919-1936 Ellison, Lee, and O'Rourke (2024); 1947-1955 IFS (print); 1956-2022 IFS (online)
- **Price index:** 1919-1936 Ellison, Lee, and O'Rourke (2024); 1947-1955 IFS (print); 1956-2022 IFS (online)

Denmark

- **Production index:** 1921-2021 Composite Industrial Production Index from Abildgren (2017)
- **Price index:** 1914-1944 retail prices, LoN-CFS; 1947-1955 IFS (print); 1956-2022 IFS (online)

Finland

- **Production index:** 1927-1936 Ellison, Lee, and O'Rourke (2024); 1948-1952 IFS (print); 1955-2022 IFS (online)
- **Price index:** 1923-1944 retail prices, LoN-CFS; 1948-1952 IFS (print); 1955-2022 IFS (online)

France

- **Production index:** 1919-1980 Villa (1993); 1980-2022 IFS (online)
- **Price index:** 1919-1980 Villa (1993); 1980-2022 IFS (online)

Germany

- **Production index:** 1914-1936 Ellison, Lee, and O'Rourke (2024); 1950-1955 IFS (print); 1956-2022 IFS (online)

- **Price index:** 1919-1940 LoN-CFS; 1947-1955 IFS (print); 1956-2022 IFS (online)

Italy

- **Production index:** 1947-1955 IFS (print); 1956-2022 IFS (online)
- **Price index:** 1921-1942 retail prices, LoN-CFS; 1947-1955 IFS (print); 1956-2022 IFS (online)

Netherlands

- **Production index:** 1919-1936 Ellison, Lee, and O'Rourke (2024); 1947-1955 IFS (print); 1956-2022 IFS (online)
- **Price index:** 1919-1936 Ellison, Lee, and O'Rourke (2024); 1957-2022 IFS (online)

Norway

- **Production index:** Ellison, Lee, and O'Rourke (2024); 1947-1955 IFS (print); 1956-2022 IFS (online)
- **Price index:** 1921-1941 retail prices, LoN-CFS; 1950-2022 IFS (online)

Portugal

- **Production index:** 1947-1950 IFS (print); 1951-2022 IFS (online)
- **Price index:** 1929-1944 LoN-CFS; 1947-1955 IFS (print); 1956-2022 IFS (online)

Spain

- **Production index:** 1946-1953 IFS (print); 1957-2022 IFS (online)
- **Price index:** 1922-1942 LoN-CFS; 1946-1953 IFS (print); 1957-2022 IFS (online)

Sweden

- **Production index:** 1925-1934 Ellison, Lee, and O'Rourke (2024); 1946-1954 IFS (print); 1959-2022 IFS (online)
- **Price index:** 1901-2022 Waldenström (2014)

Switzerland

- **Production index:** 1925-1934 Ellison, Lee, and O'Rourke (2024); 1960-2022 Index of retail sales (FRED FED)[11]
- **Price index:** 1921-1940 LoN-CFS; 1947-1955 IFS (print); 1956-2022 IFS (online)

United Kingdom

- **Production index:** 1891-2017 Bank of England, A millennium of macroeconomic data https://www.bankofengland.co.uk/statistics/research-datasets
- **Price index:** 1891-2017 Bank of England, A millennium of macroeconomic data https://www.bankofengland.co.uk/statistics/research-datasets

[11] Organization for Economic Co-operation and Development, Sales: Retail Trade: Total Retail Trade: Value for Switzerland [CHESLRTTO02IXOBSAM], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/CHESLRTTO02IXOBSAM