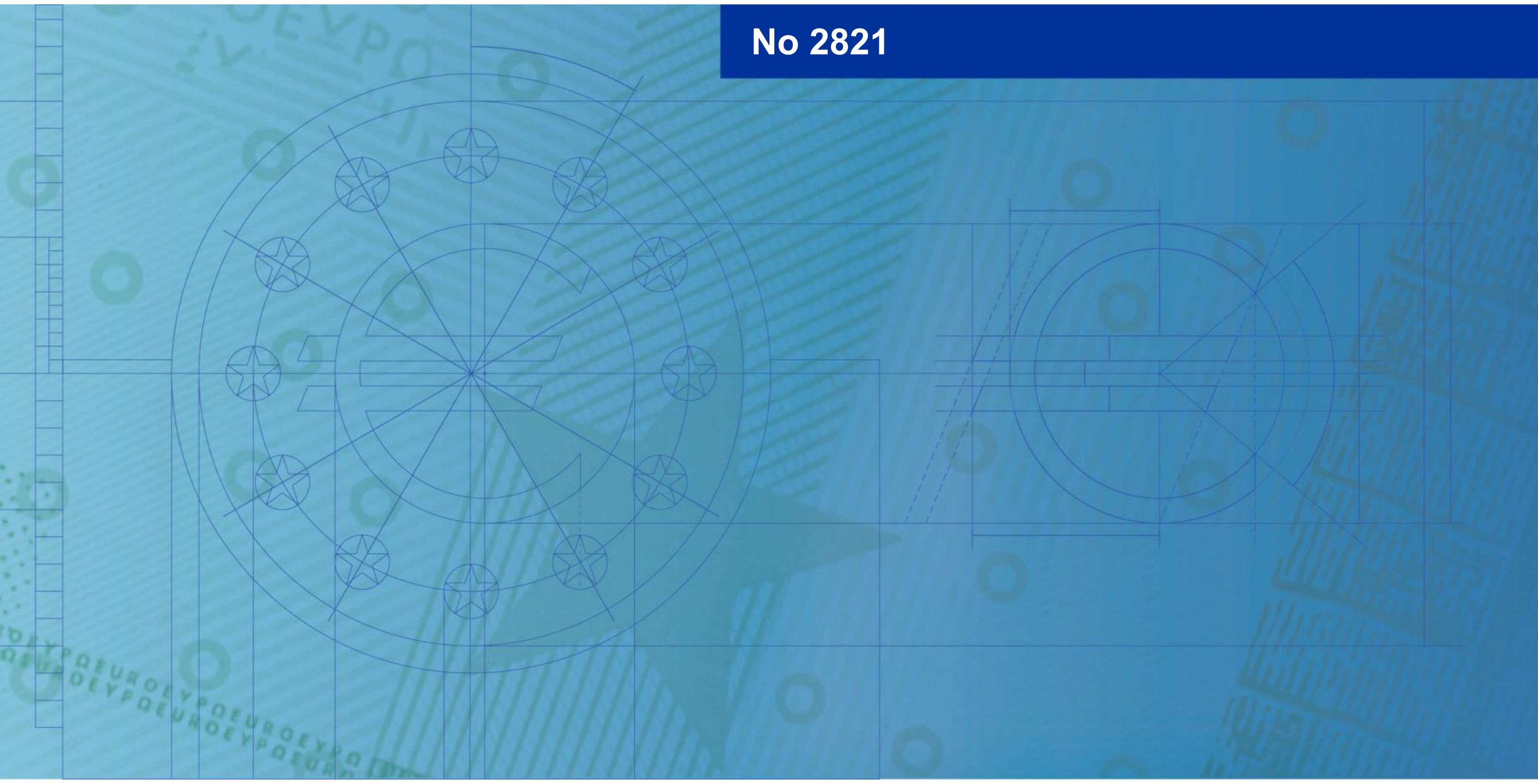
EUROPEAN CENTRAL BANK
EUROSYSTEM

Working Paper Series

Maximilian Kotz, Friderike Kuik, Eliza Lis, Christiane Nickel

The impact of global warming on inflation: averages, seasonality and extremes



No 2821

Disclaimer: This paper should not be reported as representing the views of the European Central Bank (ECB). The views expressed are those of the authors and do not necessarily reflect those of the ECB.

Abstract

Understanding of the macroeconomic effects of climate change is developing rapidly, but the implications for past and future inflation remain less well understood. Here we exploit a global dataset of monthly consumer price indices to identify the causal impacts of changes in climate on inflation, and to assess their implications under future warming. Flexibly accounting for heterogenous impacts across seasons and baseline climatic and socio-economic conditions, we find that increased average temperatures cause non-linear upwards inflationary pressures which persist over 12 months in both higher- and lower-income countries. Projections from state-of-the-art climate models show that in the absence of historically un-precedented adaptation, future warming will cause global increases in annual food and headline inflation of 0.92-3.23 and 0.32-1.18 percentage-points per year respectively, under 2035 projected climate (uncertainty range across emission scenarios, climate models and empirical specifications), as well as altering the seasonal dynamics of inflation. Moreover, we estimate that the 2022 summer heat extreme increased food inflation in Europe by 0.67 (0.43-0.93) percentage-points and that future warming projected for 2035 would amplify the impacts of such extremes by 50%. These results suggest that climate change poses risks to price stability by having an upward impact on inflation, altering its seasonality and amplifying the impacts caused by extremes.

JEL: Q54, E31, C33
Keywords: climate change, climate physical risk, inflation dynamics

Non-technical summary

As one of the major challenges of the 21st Century, researchers have illuminated the many ways in which climate change threatens human welfare, as well as the large societal transformations required to prevent these risks from intensifying further. Central banks are paying increasing attention to the importance of these physical and transition risks, including for price stability. Yet, research on the role of physical climate risks for inflation is still in its infancy. In particular, estimates of the impact on future inflation from projected climate change are lacking. This constitutes a barrier to effective and balanced assessments of both physical and transition risks related to climate change. This study addresses these issues by providing empirical estimates of historical climate impacts on inflation and combining them with state-of-the-art physical climate models to estimate the implications for inflation from projected future warming.

We draw on and expand the growing empirical literature on climate-inflation impacts, using a dataset of monthly consumer price indices across 121 countries, to flexibly identify the impacts of a variety of climate indices across different seasons and regions. We find non-linear, persistent impacts of increasing average temperatures in both higher- and lower-income countries, as well as impacts from other climate variables with differing magnitudes and persistence dependent on regional socio-economic and climatic conditions. These results are robust to a number of different empirical specifications.

Combining these empirical estimates with projections from state-of-the-art climate models, we find that future warming will cause global increases in annual food and headline inflation of 0.92-3.23 and 0.32-1.18 percentage-points per-year by 2035 respectively (uncertainty range across emission scenarios, climate models and empirical specifications). These impacts vary across regions with generally larger impacts in the global south. At high latitudes impacts show a strong seasonality, with considerably larger impacts in the summer leading to alterations of the seasonal inflation cycle. Finally, we estimate the impacts of the 2022 summer (June-July-August) extreme heat in Europe, finding that it cumulatively increased food inflation by 0.67 (0.43-0.93) percentage-points. The impacts from an equivalent extreme would be amplified by 50% under 2035 projected warming.

1 Introduction

The effects of climate change on the economy are becoming increasingly well understood. Empirical analyses have demonstrated impacts on labour productivity (Dasgupta et al., 2021), agricultural output (de Lima et al., 2021; Moore et al., 2017a, 2017b), energy demand (Auffhammer et al., 2017; Wenz et al., 2017), and human health (Guo et al., 2016; Song et al., 2017) from changes in historical climate. The resulting consequences for macroeconomic production have also been elucidated, with non-linear impacts of average temperature (Burke et al., 2015; Dell et al., 2012; Kalkuhl and Wenz, 2020), temperature variability (Kotz et al., 2021), and various aspects of precipitation (Kotz et al., 2022) identified on aggregate economic output in historical data. The future climate change expected due to greenhouse gas emissions imply considerable welfare losses when evaluated through both these micro- (Bressler, 2021; Moore et al., 2017a; Rode et al., 2021) and macro-economic impact channels (Burke et al., 2018, 2015; Kalkuhl and Wenz, 2020; Moore and Diaz, 2015).

Despite these advances, the implications of these climate impacts for inflation remain understudied. Advancing this understanding is crucial to a comprehensive assessment of climatic risks because rising or unstable prices threaten economic (Chu and Lai, 2013; Dotsey and Ireland, 1996) and human welfare (Gazdar and Mallah, 2013; Nord et al., 2014) as well as political stability (Abaidoo and Agyapong, 2022) . The 2022 cost of living crisis provides an example of such implications, with UN estimates suggesting that an additional 71 million people may fall into poverty due to rapidly rising prices (Molina et al., 2022; Lagarde, 2022). Moreover, the potential for climate change to impact inflation dynamics is of increasingly high-relevance for the conduct of monetary policy and for central banks' ability to deliver on their price stability mandate in the future (Bolton et al., 2020; Boneva et al., 2021; Drudi et al., 2021). A comprehensive assessment of climatic risks on inflation is therefore an important element in guiding the mitigation and adaptation efforts of governments, as well informing monetary policy concerning the risks posed by climate change.

Recent work has begun to shed some light on the links between climate and inflation, typically exploiting the panel structure of national inflation data and using weather changes as exogenous shocks. Studying the potential effects of various disasters on consumer price inflation, Parker, 2018 found historical impacts of storms and floods on inflation. Focusing on large temperature deviations as exogenous shocks, Faccia et al., 2021 identified short-term inflationary impacts from hot summers with stronger effects in emerging market economies. Mukherjee and Ouattara, 2021 study the effects of changing annual temperatures, finding impacts which persist for a number of years. Ciccarelli et al., 2023, took a VAR approach to study the effects of different temperature shocks in the four largest euro area economies on prices. They found upward impacts on inflation from increasing average temperatures in summer, which are more expressed in warmer countries, and upward impacts on inflation from increasing temperature variability. Regarding other variables asides from temperature, Moessner, 2022 found non-linear impacts of annual precipitation changes. Here, we extend this emerging literature along two perspectives. First, we provide an assessment of the global historical inflationary impacts arising from a wide range of shocks to different climate variables. We focus on month-on-month price changes, allowing us to flexibly account for the heterogeneity of impacts from weather shocks across seasons and regions given different baseline climatic and socio-economic conditions. Moreover, the second key contribution of our assessment is the combination of our empirical results with projections from physical climate models to estimate the inflationary impacts caused by future warming.

We combine measures of national exposure to different climate conditions based on high-resolution climate data, with a global dataset on monthly price indices for different aggregates of goods and services across 121 countries of the developed and developing world (Osbat and Parker, forthcoming). The availability of monthly price indices allows a detailed assessment of the temporal dynamics of inflationary responses to climate shocks, as well as the heterogeneity of such effects across seasons. National-level economic exposure to climate shocks is estimated based on the proportion of population exposed to different climatic indices in a given month. Deviations of monthly mean temperature and daily temperature variability, as well as excess wet and drought conditions and extreme daily rainfall (see section 2.3 for full definitions) are the main impact channels for which we identify statistically significant impacts.

Our empirical framework assesses the causal effects of these climatic measures on national, month-on-month inflation rates (measured as the change in the logarithm of price indices) by exploiting within-country variation using fixed-effects panel regression models. Country fixed effects account for unobserved differences between regions such as baseline climate and inflation rates, while the use of year fixed effects accounts for contemporaneous global shocks to both variables such as El Nino events or global recessions. We further include country-month fixed effects to account for country specific seasonality – a crucial step given the strong seasonal cycle in both monthly inflation and climate data. Furthermore, our baseline specification accounts for country specific time trends to avoid spurious correlations arising from common trends. Consequently, our framework accounts for a wide variety of un-observed confounders, and our results stem from the deviations of climate conditions from their national and seasonal patterns which cannot be accounted for by global shocks or country-specific trends. Combined with the exogenous nature of the realisation of monthly climate variables, these methodological choices strengthen confidence in a causal interpretation of our results (Auffhammer et al., 2020).

The rest of this paper is structured as follows. Section 2 provides a more detailed description of our data and methods; section 3 describes the empirical results for the response of inflation to historical climate shocks; section 4 introduces estimates of the average effect on inflation from projected future warming while section 5 assesses the implications for inflation seasonality; section 6 estimates the impacts of the 2022 European extreme summer heat on inflation and assesses how these impacts would be amplified under future warming. Finally, we conclude with a discussion of the implications and limitations of our results in section 7.

2 Data and Methods

2.1 Inflation data

Data on national-level inflation of different price aggregates is obtained from a dataset compiled by Osbat and Parker, forthcoming. The data used here constitute monthly, non-seasonally adjusted prices at different levels of aggregation. Data are available for 121 countries with varying temporal coverage from 1991-2020. The countries included cover most of the developed world (minus Australia and New Zealand where monthly data are not available), as well as large parts of the developing world. Coverage across South America and Africa is good, but large gaps exist in South-East Asia where detailed information on price aggregates are not available. Month-on-month inflation rates are used as the main dependent variable, estimated as the first difference in the logarithm of the consumer price index (CPI).

In a robustness test we alternatively use monthly inflation data from the World Bank. Differences in the aggregation procedures exist and are documented in Osbat and Parker, forthcoming. Two important differences are the inclusion of imputed rents in some headline inflation indices in the World Bank data and differences in the aggregation of food. We use the data compiled by Osbat and Parker, forthcoming as our main specification because the inclusion of imputed rents may bias estimates away from the impacts on widely consumed goods and services. In those countries where imputed rents are incorporated, they typically have a large weight, but there are many indices that do not incorporate them, notably including all European countries using the Harmonised Index of Consumer Prices. We find that the impacts on food inflation are qualitatively and quantitatively consistent when using World Bank data. The response of headline inflation differs considerably, likely due to the inconsistent inclusion of imputed rents in headline inflation in the World Bank data.

2.2 Climate data

The primary source of climate data for this study is the ERA-5 reanalysis of historical observations (Hersbach et al., 2018, 2020). ERA-5 combines satellite and in-situ observations with state-of-the-art assimilation and modelling techniques to provide estimates of climate variables with global coverage and at 6-hourly resolution. Daily 2m air temperature and surface precipitation rates for the years 1990-2020 are used as well as monthly average temperature for the recent months of June, July and August in 2022. All data from ERA-5 is obtained on a regular 0.25-by-0.25-degree grid for the years 1990-2020. For the estimates of SPEI, we follow the literature (Vicente-Serrano et al., 2010) in using monthly mean temperature and monthly precipitation totals from the CRU TS v4.05 for the years 1901-2020. This data is obtained at the same resolution and on the same grid as ERA-5.

2.3 Climate variables

Monthly, m, averages, $\bar{T}_{x,m}$, and standard deviations, $\tilde{T}_{x,m}$, of daily ERA-5 temperatures are calculated at the grid cell, x, level. Moreover, the relative exceedance of certain high precipitation thresholds, T_x, are calculated according to

$$\hat{P}_{x,m} = \sum_{d=1}^{D_m} \frac{P_{x,d}-T_x}{T_x} H(P_{x,d} - T_x) \qquad \textbf{(1)}$$

where $P_{x,d}$ are daily precipitation totals, H the Heavide step function and D_m the number of days in a given month. Following Kotz et al., 2022, precipitation thresholds are estimated as different percentiles of the local distribution of daily rainfall (1990-2020).

Standardised Precipitation Evapotranspiration Indices (SPEI) are calculated following the methods of reference (Vicente-Serrano et al., 2010), applying their publicly available code to monthly temperature and precipitation data from CRU TS v4.05. The SPEI calculation is based on a physical model of moisture balance and considers contributions to dry or wet conditions from both temperature and precipitation. It is a widely used tool to flexibly compare dry and wet conditions across countries. Moreover, its flexible estimation over different timescales allows exploration of different impact-relevant timescales. We estimate SPEI at one, two-, three-, six- and twelve-month timescales to flexibly assess the impacts of shocks across these timescales.

2.4 Spatial aggregation

We use gridded population estimates from the History database of the Global Environment (HYDE)(Klein Goldewijk et al., 2011) to estimate national-level exposure to changes in these climate variables. The data are provided at 0.25-by-0.25-degree resolution by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Monthly average temperature, temperature variability and the measure of daily precipitation extremes are aggregated to the national level by a simple population weighted average. In this weighting we also account for the proportion of grid-cells falling within a given administrative units, estimated by evenly distributing 100 points within each grid-cell and estimating the proportion which fall within the given administrative unit. Given these weightings, $w_{x,n}$, for all $\boldsymbol{N_x}$ grid-cells falling at least partially within the administrative boundary of a country, c, this weighted average reads:

$$\bar{T}_{c,m} = \frac{1}{N_x}\sum_{x=1}^{N_x} \bar{T}_{x,m} w_{x,c} \qquad \textbf{(2)}$$

for monthly average temperature for example. The equivalent procedure is applied to temperature variability and the measure of daily precipitation extremes.

For SPEI, we first estimate binary variables indicating whether a grid cell is experiencing conditions which exceed a certain level of dry or wet (indicated as $SPEI <$ $and\; SPEI >$, respectively in equation 3). We choose thresholds of one, one-point-five, two and two-point-five deviations to flexibly assess the exceedance of different thresholds. We then apply the same spatial aggregation procedure as outlined in equation 2 to estimate the proportion of population exposed to these excessively wet or dry conditions.

The magnitude of the temperature seasonal cycle, $\hat{T}_c$ is estimated from national monthly temperatures which are then averaged over the historical period (1990-2020) before use in the regression models. Deviations of average temperature, $\boldsymbol{d\bar{T}_{c,m}}$, and temperature variability, d$\tilde{T}_{c,m}$, from their historical average (1990-2020) are also calculated for use as dependent variables.

2.5 Empirical framework for estimation of causal effects

We apply fixed-effects panel regression models to identify the causal effects of changes in climate variables on national level inflation. Month-on-month national level inflation rates, $dlCPI_{c,m}$ are the dependent variable. Deviations of average temperature are included with an interaction with the average temperature level, whereas deviations of temperature variability are included with an interaction with the magnitude of the seasonal temperature cycle following previous work (Kotz et al., 2021). Daily precipitation extremes are included with an interaction with the monthly average temperature level (having also tested alternative interactions with the monthly share of annual precipitation). Both positive (excess wet) and negative (excess dry) SPEI threshold exceedance are used. For the former we find no significant effect of interactions with the monthly average temperature level or the monthly share of annual precipitation and as a result include no interactions in our main specification. For the latter we find a significant effect of an interaction with monthly average temperature level and therefore include this in our main specification. We include all climate variables simultaneously to ensure that any effects we identify occur independently of one another and are therefore additive (Auffhammer et al., 2020; Kotz et al., 2021). Each climate variable is included with 11 lags in addition to the contemporaneous term, to assess the delayed effects of monthly climate shocks over the course of the following year.

Our baseline specification includes country, μ_c, year, η_y, and country-month, $\pi_{c,m}$, fixed effects, in addition to country specific linear time-trends, $\gamma_c y$. Country fixed effects account for unobserved differences between regions such as baseline climate and inflation rates, while the use of year fixed effects accounts for contemporaneous global shocks to both variables such as El Nino events or global recessions. The inclusion of country-month fixed effects accounts for country specific seasonality – a crucial step given the strong seasonal cycle in both monthly inflation and climate data. This constitutes an additionally conservative step by ignoring inflation impacts which could repeatedly occur seasonally due to seasonal changes in climate. This ensures that our results only estimate the impacts of deviations from normal conditions, both in terms of annual and seasonal conditions. Finally, our baseline specification accounts for country specific time trends to avoid spurious correlations arising from common trends. This is important given the presence of strong warming trends in the historical period which could cause spurious correlations to inflation changes. Interestingly, we find that accounting for these linear trends enhances the magnitude of estimated effects, suggesting that it indeed assists in removing estimation biases. Estimates without linear time trends are qualitatively similar. The regression model of the baseline specification then reads:

$$dlCPI_{c,t} = \sum_{L=0}^{11}(d\bar{T}_{c,t-L} + \bar{T}_{c,t-L} \,.\, d\bar{T}_{c,t-L}) + \sum_{L=0}^{11}(d\tilde{T}_{c,t-L} + \hat{T}_{c}.\, d\tilde{T}_{c,t-L}) + \sum_{L=0}^{11}(SPEI >_{c,t-L}) + \sum_{L=0}^{11}(SPEI <_{c,t-L} + \bar{T}_{c,t-L}.SPEI <_{c,t-L}) + \sum_{L=0}^{11}(\hat{P}_{c,t-L} + \bar{T}_{c,t-L}.\hat{P}_{x,t-L}) + \mu_c + \eta_y + \pi_{c,m} + \gamma_c y + \varepsilon_{c,t} \tag{3}$$

where t is the date in terms of a given year's month and $\varepsilon_{c,t}$ is the country-date residual error. Note that here m refers to the general date i.e., the month of a specific year, except in the fixed effects terms where m refers to all general occurrences of a particular month, and y refers to the particular year. In our baseline specification, errors are clustered by country.

In alternative robustness tests we estimate a dynamic model in which we also include 11 lags of the inflation rates, $dlCPI_{c,m}$ (Table 1 Column 2), account for cross-sectionally correlated errors using Driscoll Kraay errors (Driscoll and Kraay, 1998) (Table 1 Column 3), use World Bank data on monthly inflation rates (Table 1 Column 6), and alternatively normalise monthly inflation rates by their interannual standard deviation to account for differing baseline inflation volatilities. Moreover, we also estimate models in which we include additional interactions of each climate variable with a binary term indicating whether a given country has above or below median national income per capita (based on world bank estimates of GDP and population).

2.6 Climate model data

Daily 2-m temperature and precipitation totals are taken from 21 climate models participating in CMIP-6 under the most pessimistic (RCP8.5) and most optimistic (RCP2.6) greenhouse gas emission scenario from 2015-2100. The data have been bias-adjusted and statistically downscaled to a common half-degree grid to reflect the historical distribution of daily temperature and precipitation of the W5E5 (Cucchi et al., 2020) dataset using the trend-preserving method developed by ISIMIP (Lange, 2019). Primary data on grid-cell level are publicly available for 10 models from the ISIMIP database.

2.7 Estimating impacts from projected future warming

To assess the impact on inflation from projected future warming, we first estimate future warming at the country level from each climate model. To do so, we take the difference between 30-year averages of country-level monthly temperatures centered on the future period in question (2035 or 2060) and 30-averages over the historical period of 1991-2020. The impacts on inflation arising from these future monthly temperatures are then calculated by evaluating the first terms of equation 3 which pertain to monthly average temperatures. This produces 12 months of lagged impacts from each month under future warming. These lagged impacts are then aggregated, avoiding double counting impacts which fall in the proceeding calendar year.

We also assess the impacts of the 2022 extreme summer heat in Europe using ERA-5 estimates of monthly temperatures in June, July and August. The same procedure as described above is applied to these monthly temperatures to estimate the historical inflationary impacts of these three months. To then assess the amplification of impacts from such extremes under future warming, we evaluate the future warming occurring between 2022 and 2035 or 2060 (using the difference between 30-year averages of temperature centred on 2022 and 2035 or 2060 in each climate model and scenario). This additional month-specific warming is then added on to the historically observed 2022 summer temperatures, and the impacts on inflation evaluated as before. This approach assumes that future warming will shift the mean of the distribution of possible summer temperatures and does not account for the potential role of changing temperature variability in altering future temperature extreme intensity. However, evidence for a role of temperature variability in enhancing extremes at monthly time-scales is limited (Lenton et al., 2017; van der Wiel and Bintanja, 2021).

Uncertainty in estimated impacts under projected climate arises from a combination of factors, including the choice of empirical specification, the range of climate model projections, as well as future emission scenarios if not explicitly comparing their differences. We report estimates with an uncertainty range accounting for these contributing factors. This uncertainty range spans the lowest estimates across empirical specifications (and emission scenario unless explicitly comparing their differences) combined with the lower range of climate model projections (the mean minus one standard deviation of impacts across climate models), and the largest projection across empirical specifications combined with the higher range of climate model projections (the mean plus one standard deviation of impacts across climate models). This framework provides a transparent assessment of uncertainty across a range of factors.

3 The response of inflation to historical changes in climate

We find a rich response of inflation in different price aggregates to a variety of climatic measures (Fig. 1). Concerning headline inflation, the response to average monthly temperature increases is non-linear, such that temperature increases in hotter months and regions cause larger inflationary impacts. This finding is consistent with previous results (Ciccarelli et al., 2023 ; Faccia et al., 2021; Mukherjee and Ouattara, 2021), but by using interaction terms our framework allows a flexible and unifying description of this heterogeneity across both seasons and regions. This non-linearity is such that increases in average temperatures in the hottest month of the year cause upwards inflationary pressures in all regions of the world as well as in the coldest months at lower latitudes. At higher latitudes, the effects of a temperature increase in the coldest months is mostly negligible and can even be negative at the highest latitudes (Fig. S1). By using lagged climate measures, we find that the impacts of a 1C increase in monthly temperature persist across the entire twelve months following the initial shock (Fig. 1), causing a cumulative effect of 0.17 percentage-points over the following year (under our central specification shown in column 1 of Table 1).

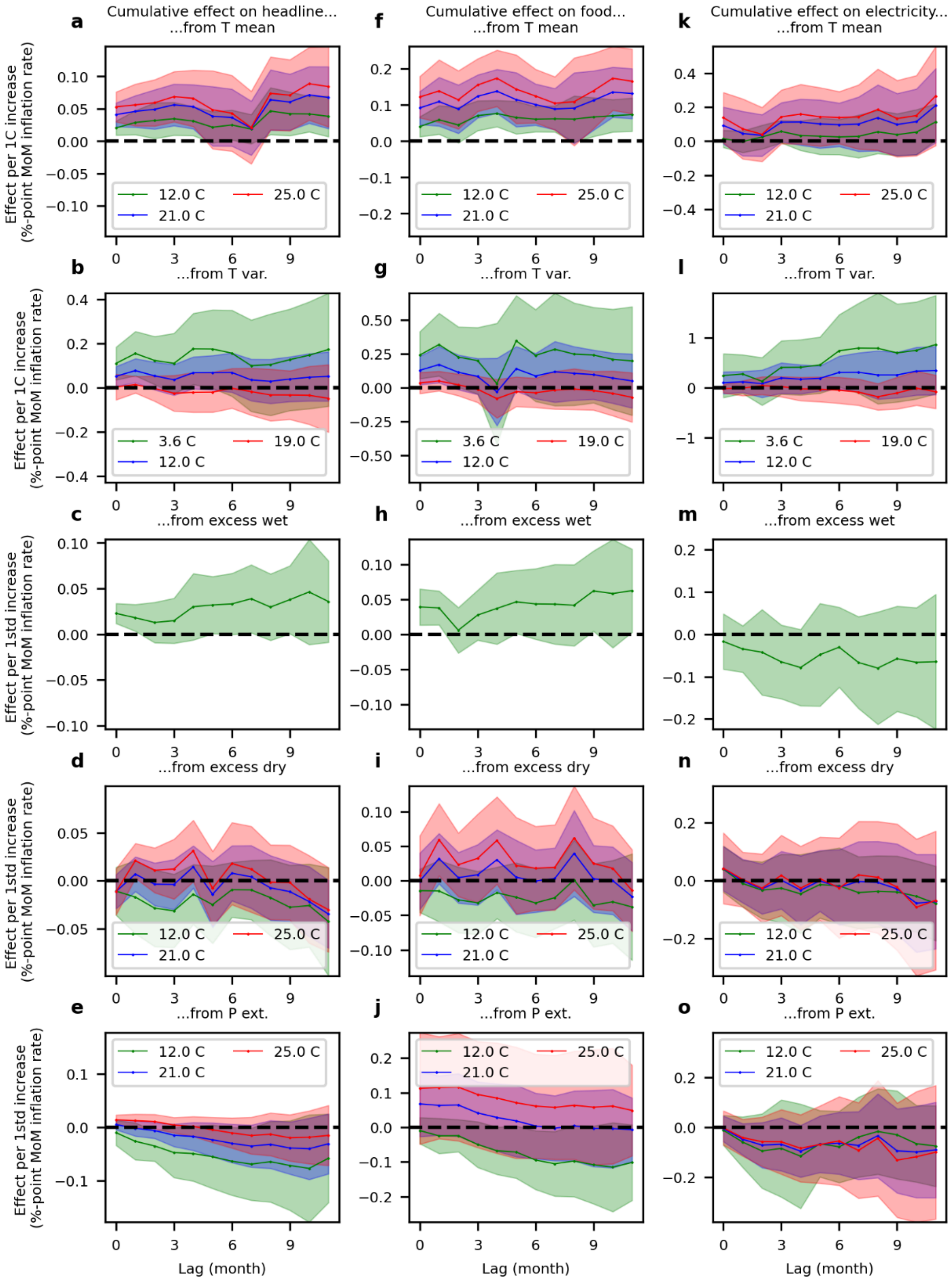


Figure 1. The response of inflation in three price aggregates to monthly climate shocks.

Plots show the cumulative causal effect of a climatic change on month-on-month inflation rates in headline (a-e), food (f-j) and electricity (k-o) price aggregates at different times after the initial shock, as estimated from fixed-effects panel regression models (see section 2.5). The effects on inflation due to deviations of monthly mean temperatures from their historical (1990-2020) average, deviations of the variability of daily temperatures from their historical (1990-2020) average, national exposure to excess wet (measured as the proportion of national population exposed to a standardised precipitation-evapotranspiration index (SPEI) of greater than 1-std), to excess dry (SPEI less than1std) and to extreme daily rainfall (defined to account for both extreme frequency and intensity based on regional percentiles, see section 2.3), are shown from top to bottom, having accounted for all measures simultaneously in the regression models. Effects are shown per 1C increase or per 1-std increase for the temperature and precipitation metrics respectively. The effects of mean temperature, excess dry and extreme precipitation are moderated by interactions with the monthly average temperature, and as such the effects are shown separately at the upper and lower quartiles and the median of observed temperatures, the values of which are shown in the legend of each panel. The effect of temperature variability is moderated by an interaction with the magnitude of the seasonal temperature cycle, and effects are shown at the corresponding upper and lower quartiles and the median of observed seasonal magnitudes. No significant interactions are found for impacts from exposure to excess wet. Points and lines show central estimates while error bars show 95% confidence intervals when clustering standard errors by country.

In addition to the impacts arising from average temperatures, we also assess impacts from daily temperature variability (the standard deviation of daily temperatures within each month, see section 2.3). We find upwards pressures on inflation which depend on the magnitude of the seasonal cycle, with larger impacts at lower latitudes where the seasonal cycle is less pronounced, reflecting the same patterns of vulnerability identified from the impacts of daily variability on economic growth (Fig. 2c) (Kotz et al., 2021). These impacts also persist over twelve months, although with increasingly large errors.

To assess impacts from exposure to abnormal precipitation conditions, we use the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). This measure accounts for contributions to moisture balance from both precipitation and temperature changes flexibly across different timescales. By calculating the grid-cell level exceedance of certain SPEI thresholds and aggregating the proportion of national population exposed to these excess wet or dry conditions, we aim to limit the issue of spatially averaging over opposing effects. This is particularly relevant for precipitation given its larger spatial variability (Auffhammer et al., 2020). Using a time scale of two months and an exposure-threshold of one standard deviation, we find that excess wet conditions cause upwards impacts on inflation which persist over twelve months, independent of baseline climate conditions (Fig. 1). Excess dry conditions have some significant upwards impacts when occurring in hot months or regions, but these are generally less persistent or significant (Fig. 1). These results are qualitatively consistent under different SPEI timescales and thresholds (see SI Fig. S2). We further consider the impacts of daily precipitation extremes (defined as population exposure to the grid-cell level relative exceedance of the 99th percentile, see section 2.3) to assess potential heavy-precipitation impacts arising over shorter timescales such as flooding (Kotz et al., 2022). Statistically significant inflationary pressures can be identified in hot months in the first month following the shock, but these impacts appear not to persist with insignificant cumulative impacts at further time-horizons.

Assessing different price aggregates, we find that the effects on headline inflation predominantly arise through food inflation (Fig. 1f-j, see Fig. S3 for other price aggregates). Impacts in food inflation are approximately twice as large, likely reflecting, besides a generally greater volatility in food inflation, the greater vulnerability of the agricultural sector to climatic shocks (Fig. S4 shows that the differential impacts on food and headline inflation persist when assessing normalised CPI data). Impacts on food inflation are likely to arise through supply-side mechanisms given the considerable evidence for impacts on agricultural production from changes in mean temperature (de Lima et al., 2021; Moore et al., 2017b), temperature variability (Semenov and Porter, 1995; Wheeler et al., 2000) as well as precipitation characteristics (Damania, 2020; Liang et al., 2017). Further work would however be required to elucidate these mechanisms explicitly. We also find some impacts of average temperature and temperature variability on electricity inflation, although with larger errors. This may reflect the fewer observations in this more detailed price aggregate as well as a relatively weaker signal. Nevertheless, the response of electricity prices to temperature is consistent with micro-economic evidence of effects of temperature on the demand for heating and cooling (Auffhammer et al., 2017; Wenz et al., 2017).

Mean temperature impact on food inflation	1 Central	2 Dynamic panel	3 Driscoll-Kray errors	4 Higher-lower- income split		5 Higher-lower-income split + normalised		6 World bank data
				Higher-income	Lower-income	Higher-income	Lower-income	
Instantaneous monthly impact								
at 21C	0.09% (0.05, 0.14)	0.08% (0.03, 0.13)	0.08% (0.04, 0.12)	0.07% (0.003, 0.051)	0.14% (0.07, 0.21)	0.06 stds (0.03, 0.09)	0.10 stds (0.70, 0.14)	0.11% (0.06, 0.15)
at 25C	0.12% (0.07, 0.18)	0.11% (0.05, 0.17)	0.11% (0.06, 0.16)	0.09% (0.04, 0.14)	0.19% (0.11, 0.28)	0.09 stds (0.04, 0.12)	0.14 stds (0.10, 0.17)	0.13% (0.08, 0.18)
Cumulative 12-month impact								
at 21C	0.13% (0.06, 0.20)	0.18% (0.03, 0.33)	0.18% (0.02, 0.34)	0.17% (0.09, 0.25)	0.12% (0.004, 0.24)	0.16 stds (0.09,0.23)	0.11 stds (0.03, 0.19)	0.09% (0.01, 0.17)
at 25C	0.17% (0.08, 0.26)	0.23% (0.04, 0.42)	0.23% (0.03, 0.43)	0.22% (0.13, 0.32)	0.11% (-0.04, 0.27)	0.21 stds (0.12, 0.30)	0.11 stds (0.002, 0.21)	0.12% (0.02, 0.22)
Impact under projected climates								
Projected global average annual impact under SSP585 by 2035	1.79% (1.24, 2.33)	2.48% (1.72, 3.24)	2.48% (1.72, 3.24)	1.65% (1.16, 2.14)		1.60% (1.16, 2.04)		1.10% (0.63, 1.20)
Difference SSP585-SSP126 at 2060	2.14% (1.56, 2.73)	3.01% (2.17, 3.84)	1.87% (1.38, 2.36)	1.87% (1.38, 2.36)		1.87% (1.39, 2.35)		1.42% (1.00, 1.85)
Details of the empirical specification, accounting for…								
Country, year and country-month fixed-effects	Yes	Yes	Yes	Yes		Yes		Yes
Country-specific time trends	Yes	Yes	Yes	Yes		Yes		Yes
Dynamic lags	No	Yes	Yes	No		No		Yes
Cross-sectionally correlated errors	No	No	Yes	No		No		No
Different economic development	No	No	No	Yes		Yes		No
Different baseline inflation volatilities	No	No	No	No		Yes		No
Inflation data	Osbat and Parker	Osbat and Parker	Osbat and Parker	Osbat and Parker		Osbat and Parker		WB

Table 1: Robustness of the impact of mean temperature on food inflation (see next page)

Table 1 (cont.). Robustness of the impact of mean temperature on food inflation to the empirical specification. The table provides an overview of alternative econometric specifications conducted as robustness tests which include different methodological techniques and datasets. Results of the historical monthly impacts identified empirically are shown in the first four rows. The fifth row shows the projected annual impacts under each specification by 2035 under a high emission scenario (SSP585), and the sixth row shows the difference between the high (SSP585) and low (SSP126) emission scenarios by 2060. Point estimates are shown with the 95% confidence intervals in the first four rows, whereas in the fifth row point estimates plus or minus the standard deviation of climate model spread are shown. Column 4 shows results having estimated effects separately for countries dependent on above- or below-median national incomes based on WB estimates (denoted higher- or lower- income), and column 5 having normalised month-on-month inflation rates by their within-country historical standard deviation. Results are qualitatively consistent across specifications, in terms of significant instantaneous and cumulative impacts of monthly average temperatures on food inflation which are stronger at higher temperatures and which cause considerable upward pressures on average inflation under future warming.

These historical impacts are robust to a number of tests and alternative specifications, an overview of which is shown in Table 1 concerning mean temperature impacts (the results for other variables can be found in Figs. S5-7). These tests include accounting for auto-correlations in inflation using a dynamic panel specification and for cross-sectionally correlated errors using Driscoll Kraay errors (Driscoll and Kraay, 1998). Moreover, we conduct tests in which we split our estimates based on above- or below-median national incomes (estimated from World Bank GDP and population data), as well as when normalising inflation data by its historical volatility. Doing so we find the effects of average temperature increases to be consistent across both higher- and lower-income countries and when accounting for different baseline historical volatility. The impacts of temperature variability are more heterogenous across income classes and price aggregates, and the effects from excess wet conditions are considerably stronger in higher-income countries (Fig. S6). The independence of the impacts of average temperature on baseline socioeconomic conditions suggests that historical adaptation to warming has been limited insofar as that adaptation is related to socioeconomic development.

4. Implications under future warming – persistent upwards pressures on inflation

This empirical evidence for historical impacts of climate shocks on inflation suggests that the ongoing warming and intensification of weather extremes and variability due to anthropogenic greenhouse gas emissions (Arias et al., 2021) may have consequences for both current and future inflation. To assess these consequences, we combine the empirical responses identified above with projections of future climate change from an ensemble of 21 bias-adjusted climate models from the Coupled Model Intercomparison Project Phase 6. We focus on the role of average temperature due to the persistence of its impacts across income groups and price aggregates (Fig. 1), as well as due to the stronger response of warming to greenhouse gas forcing compared to other climate variables. We do not introduce explicit models of future adaptation which could mitigate these impacts but note that our results do account for historical adaptations which may have evolved through prolonged exposure to different climate conditions and through differing levels of economic development. Indeed, the fact that we find larger impacts from increasing temperatures in hot regions and comparable impacts across both higher- and lower-income countries suggests that historical adaptation to temperature increases through these mechanisms has been limited. As such, we consider our estimated impacts to represent the exogenous effects of future warming on inflation which would occur in the absence of historically unprecedented adaptation such as the development of new technologies and other factors.

Estimating the net annual impacts from the average warming occurring in the next 15 to 40 years with our central empirical specification (see section 2.7) shows upwards inflationary impacts across all of the world. In a projected 2035 climate, future warming is estimated to cause persistent increases in food inflation of 1.49±0.45 or 1.79±0.54 percentage-points per-year (p.p.p.y.) respectively in an optimistic or pessimistic emission scenario on average globally (errors indicating the standard deviation across climate model projections). Impacts on headline inflation follow similar patterns and are approximately half as large, 0.76±0.23 or 0.91±0.28 p.p.p.y. under a best- or worst-case emission scenario (Fig. 3a, c). Moreover, these impacts vary quantitatively dependent on both the future emission pathways (shown in Fig. 3) and on the choice of empirical specification (shown in Table 1 and Figs. S8-10), as well as on the range of climate model projections. Uncertainty across all of these factors (see section 2.7) results in a range of potential global average annual impacts on food inflation of 0.92-3.23 p.p.p.y. by 2035, and 0.32-1.18 p.p.p.y. for headline inflation. These results therefore provide robust evidence of persistent upward pressures on inflation from projected global warming of considerable magnitudes already during the next decade, independent of future emission trajectories.

Beyond 2035 the magnitude of estimated inflation impacts diverges strongly across emission scenarios, suggesting that decisive mitigation of greenhouse gases could substantially reduce impacts. The difference in global impacts on food inflation between the highest and lowest emission scenarios is 2.1 p.p.p.y. by 2060 in our central specification, with a full uncertainty range across empirical specifications and climate models of 1.6-3.8 p.p.p.y. For headline inflation this difference is 1.1 percentage-point under our central specification, with a full uncertainty range of 0.49-1.38 p.p.p.y. (Fig. 2, Figs. S8-10, Table 1 row 6). Under an optimistic emission scenario, impacts are only marginally larger in 2060 than in 2035, but a pessimistic emission scenario would cause impacts exceeding 4 p.p.p.y. across large parts of the world across empirical specifications (Fig. 2, Figs. S8-10).

The spatial heterogeneity of inflationary impacts from projected warming is less robust across empirical specifications. Most empirical specifications estimate larger impacts across the global south compared to the global north, and the largest impacts are found across Africa and South America robustly across specifications (Figs. 2 & S8-10).[1] However, when accounting for the different response between higher- and lower-income countries (Fig. S6, column 4 of Table 1), equally large impacts are estimated for North America and Europe as in Africa and South America (Fig. S9). The extent of projected future warming is larger at higher latitudes than at low latitudes due to polar amplification (Previdi et al., 2021), appearing to counter-balance the fact that higher latitudes currently experience lower temperatures and therefore a weaker response to temperatures in this specification. However, when also accounting for different baseline historical inflation volatility (column 5 of Table 1), impacts are again larger across Africa and South America than North America or Europe (Fig. S10).

---

[1] Country-level impacts are aggregated to larger spatial regions using weighted by population (using World Bank estimates of national level population in 2017) to reflect the human exposure to future inflationary pressures.

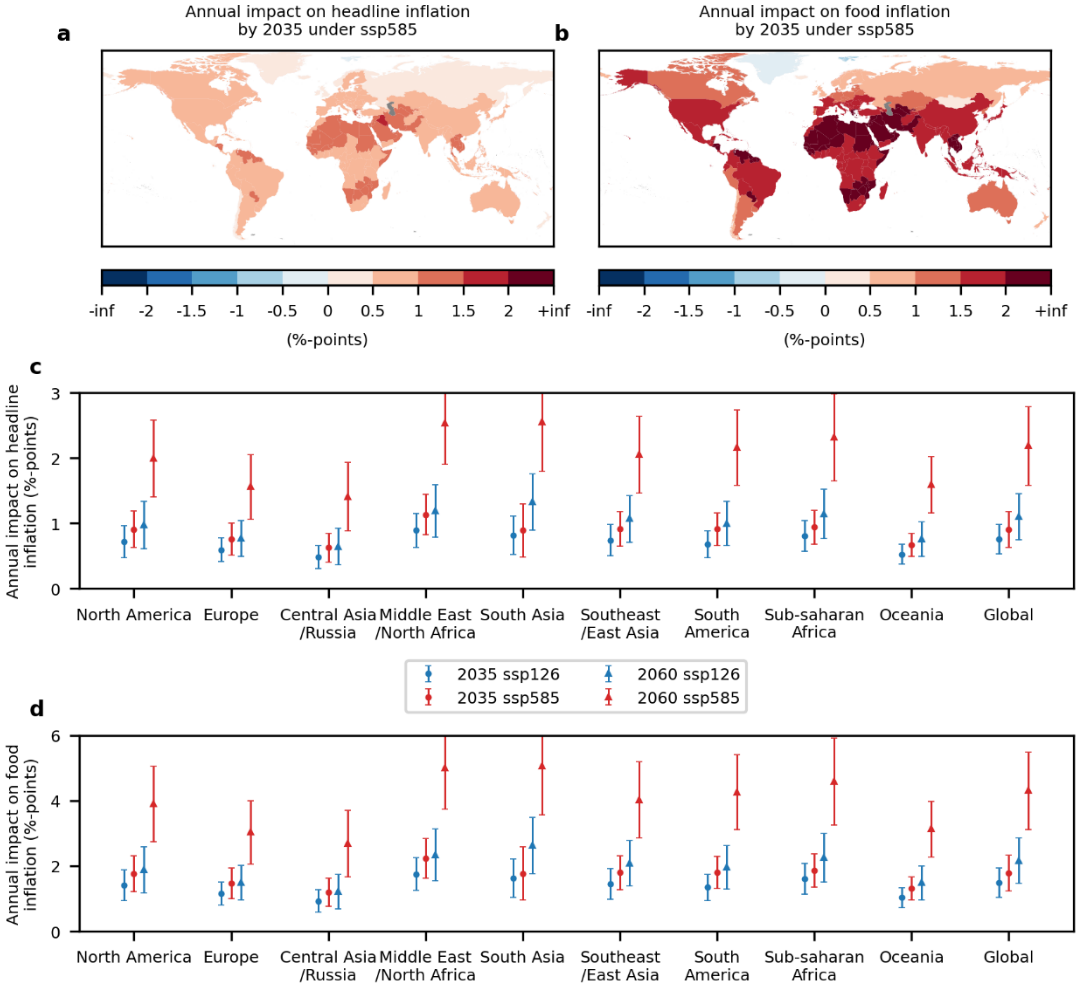


Figure 2. Estimated impacts on annual inflation rates from projected future warming. Maps of the impacts on annual national inflation from the warming expected by 2035 (assessed via 30-year averages centred on 2035) under a high-emission scenario (SSP585), as estimated from the projections of CMIP-6 climate models for headline (a) and food (b) price aggregates. Impacts are estimated accounting only for increasing average temperatures using the central specification shown in column 1 of Table 1. The annual impacts on inflation aggregated across world regions (population weighted), at different time periods (30-year averages centred on the point in question) and under both a low (SSP126) and high (SSP585) emission scenario for headline (a) and food (b) price aggregates. Point estimates show the average, and error bars the standard deviation, of impacts from the warming projected across the ensemble of 21 CMIP-6 climate models, in the absence of historically unprecedented adaptation.

5. Implications under future warming – altered seasonality

The use of monthly CPI data allows us to further assess how the estimated impacts from projected future warming are distributed across the year. Concerning food inflation, the impacts from average warming are fairly constant throughout the year across the tropics but vary considerably across seasons in Northern mid-latitudes (20-40N) where they can be twice as large in summer compared to winter (Fig. 3a).[2] At the highest latitudes (>40N) upwards impacts in summer even contrast downwards impacts in winter. This seasonal and spatial heterogeneity to the inflationary impacts of future warming is robust across empirical specifications (Figs. S11-13), although accounting for different historical baseline inflation volatilities (column 5 of Table 1) introduces some additional noise (Fig. S13). These seasonally heterogenous impacts would cause alterations to the usual seasonality of inflation, resulting in an amplification of seasonal variability across most of the global south and the USA, and reductions in seasonal variability across most of Europe (excluding Spain) and the higher northern latitudes (Figs. 3b & S11-13b). A reduction in variability occurs when higher temperatures increase month-on-month inflation rates in months with historically lower rates, compared to other months (Fig. 3d). Figs. 3c-f show examples of such impacts for a selection of countries (see Fig. S14 for further European countries). The pattern of impacts across seasons and regions is similar for headline inflation, with smaller estimated impacts (Figs. S15). These alterations to the seasonal dynamics of inflation may pose challenges to inflation forecasting, which could however be mitigated by introducing of weather variables in inflation forecast models (Vidal-Quadras Costa et al., forthcoming).

---

[2] To evaluate differences across different latitudinal zones we take binned averages across latitudinal zones to convey the relationship between latitude and the seasonality of inflation response and impacts. Countries are considered part of a latitudinal zone if their centroid falls within the zone's boundaries, and in this context, we use a raw average without population weighting to reflect the nature of this relationship between latitude and impacts rather than to reflect the average human exposure to impacts.

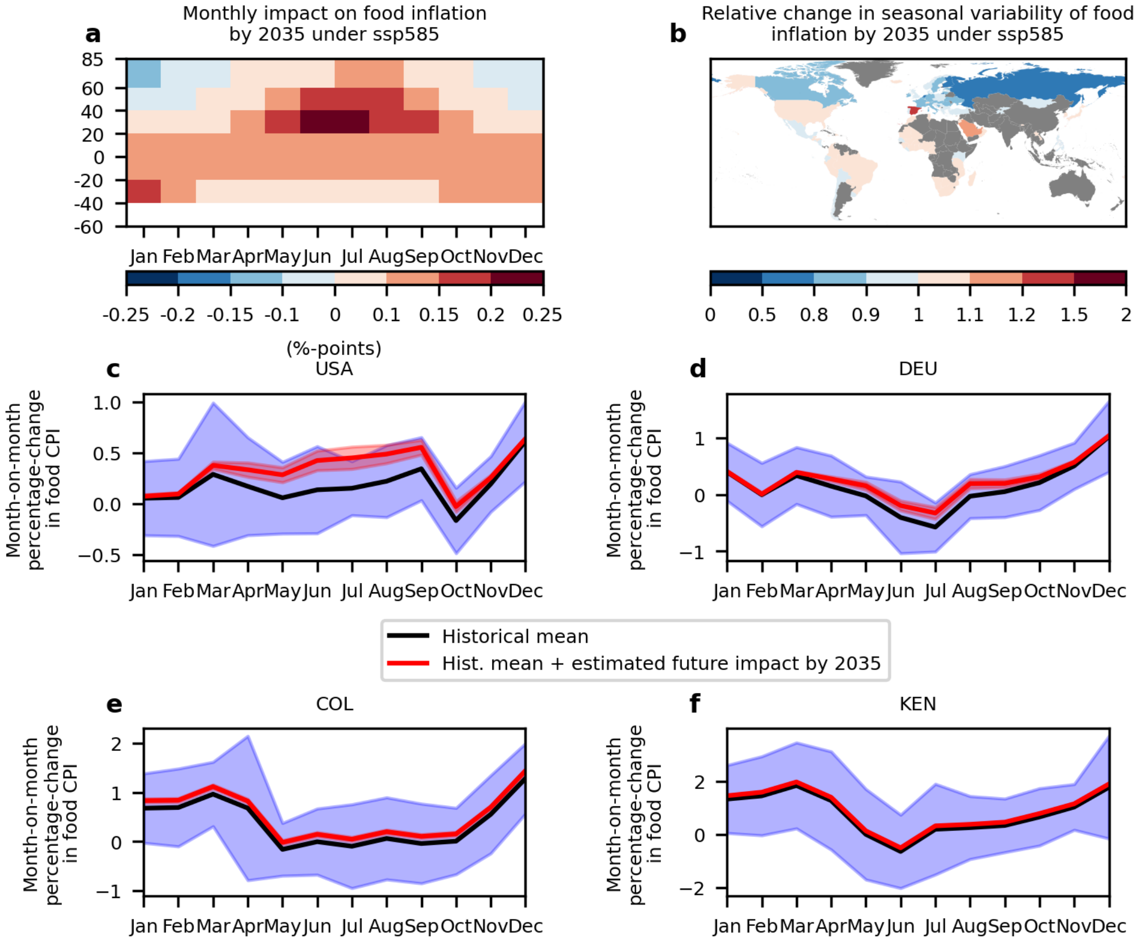


Figure 3. The estimated impacts of projected future warming on the seasonality of food inflation. (a) The average monthly impacts on food inflation across latitudinal bands estimated from the warming expected by 2035 (assessed via 30-year averages centred on 2035) under a high-emission scenario, as projected on average across the ensemble of CMIP-6 climate models. Impacts are estimated accounting only for increasing average temperatures. (b) The relative change in the seasonal variability of food inflation under future warming, estimated as the ratio of the standard deviations of future and historical average seasonal inflation cycles. (c-f) Country-specific examples of the impact on the seasonal cycle of food inflation. Black curves show the historical average month-on-month percentage change in the food consumer price index (CPI) with blue error bars showing the standard deviation across years. Red curves show this historical average cycle plus the impacts estimated from projected future warming with the error bars showing the standard deviation of projections across climate models.

6. Implications under future warming – amplified extremes

In addition to average warming trends, climate change is also altering the intensity and frequency of hot extremes which may pose additional risks compared to changes in average conditions. The heat extremes of the 2022 summer in Europe is a prominent example in which combined heat and drought had wide-spread impacts on agricultural and economic activity. These effects have likely added to recent inflationary pressures, but their exact magnitude is difficult to assess in the context of other pressures from the Russian invasion of Ukraine and the aftermath of the Covid-19 pandemic. Using ERA-5 estimates of monthly temperatures, in June, July and August we estimate that the anomalous heat over these three months alone caused a cumulative impact of 0.67 percentage-points (0.43-0.93 across empirical specifications) on annual food inflation and 0.34 percentage-points (0.18-0.41) on annual headline inflation in Europe, with larger impacts across Southern Europe (Fig. 4b shows maps of these impacts under our central empirical specification, see Figs. S16-18 for other specifications). For the euro area, we find aggregate impacts on food inflation of 0.78 p.p. in our central specification (using HICP country weights for the aggregation). Given that we find impacts from drought over the short-term but find their cumulative impacts over 12-months to be mostly negligible (Fig. 1), these figures may under-estimate the impacts of the 2022 summer combined heat and drought extreme in the short-term but are likely to be representative of the cumulative long-term impacts.

Future climate change will amplify the magnitude of such heat extremes, thereby also amplifying their potential impacts on inflation. To assess such effects, we assume that climate change will alter the distribution of future summer temperatures by shifting the mean. We therefore add the future summer warming occurring from 2022 onwards in CMIP-6 projections to the historical temperatures of 2022 and re-evaluate their impact using our empirical response functions (see section 2.7). This approach estimates that an equivalent extreme summer (i.e., in the upper tail of the temperature distribution, shifted for future climates) would have impacts on food inflation in Europe of 1.0 percentage-points (0.6-1.6, uncertainty range across climate models and empirical specifications, see also Figs. S15-17) were it to occur in 2035 under a high-emission scenario, or of 0.9 percentage-points (0.5-1.4) under a low-emission scenario (Fig. 4d), in the absence of unprecedented adaptation. In the later part of the century, the amplification of such extremes would diverge under different emission scenarios, remaining at 1.1 percentage-points (0.6-1.8) by 2060 under the most optimistic scenario compared to 1.8 percentage-points (1.0-3.2) under the most pessimistic scenario of emission mitigation. Impacts on headline inflation follow similar patterns with approximately half the magnitude (Fig. 4c). This suggests that in addition to causing persistent upward pressures on inflation, future warming will also amplify the impacts from exceptionally hot summers such as that experienced in Europe in 2022. Extremely hot summers would therefore pose increasingly important upside risks to inflation, causing challenges for inflation forecasting and, particularly under pessimistic emission scenarios, posing risks to price stability.

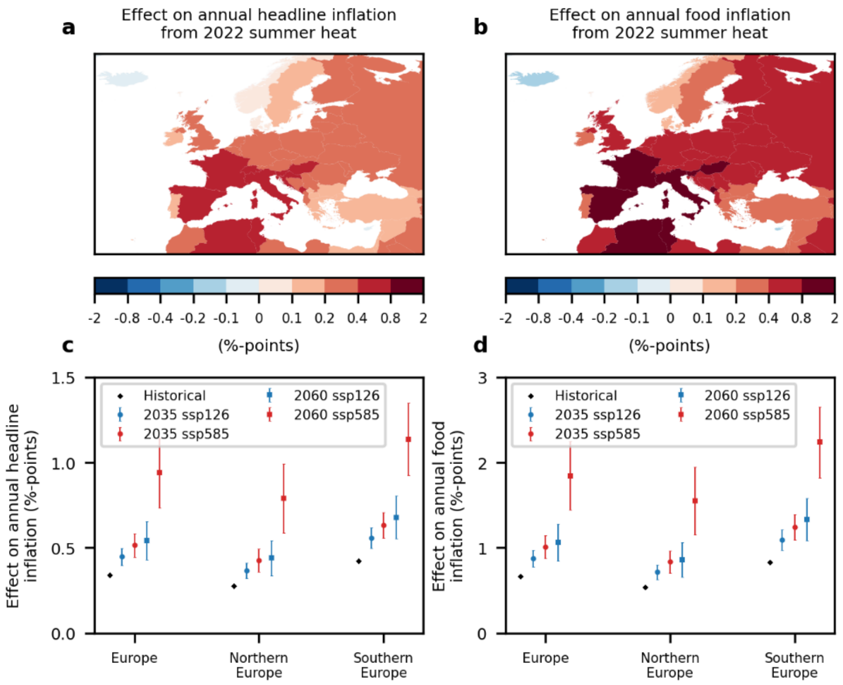


Figure 4. Estimated impacts of 2022 summer extreme heat in Europe on inflation, and the amplification of impacts from such extremes under projected future warming. (a) The cumulative impacts on headline (a) and food (b) inflation from the observed temperatures of June, July and August of 2022 across Europe. Regionally aggregated (using a population weighting) impacts on headline (a) and food (b) inflation from the historical 2022 summer temperatures, as well as those impacts which would result from such a summer when amplified by future warming (see section 2.7). Future warming by 2035 and 2060 are estimated as the difference between 30-year averages centred on the respective future time-points and 2022, using climate models of the CMIP-6 ensemble under both low (SSP126) and high (SSP585) emission scenarios. Point estimates and error bars show the mean and standard deviation of impacts across climate models.

7. Discussion

While this work has identified a number of climatic measures with significant historical impacts on headline and food inflation globally, some limitations persist in providing a comprehensive and general relationship between climate and inflation. Firstly, a comprehensive assessment is challenging due to the wide range of potential climatic sources of impacts. For example, tropical cyclones and sea level rise cause damage to infrastructure and production and are therefore potential sources of inflationary impacts of importance under both historical and future climate change. Our assessment does not explicitly account for their effects and therefore likely underestimates the possible future inflationary impacts of climate change in this regard. Future work assessing such climatic phenomena would be valuable but may face challenges due to limited extent of historical sea level rise and the smaller spatial extent of tropical cyclones. The development of datasets of consumer prices at higher spatial resolutions such as for sub-national regions may assist in the latter, as well as also improving the accuracy with which the impacts of temperature and precipitation can be identified. Indeed, precipitation changes have a higher spatial variability than temperature (Auffhammer et al., 2020) which may be a source of the large errors and lack of persistence in the precipitation impacts we identify, despite using a thresholding approach to mitigate this issue (see section 2.4). High-resolution economic data has assisted in the identification of precipitation impacts on economic output (Damania, 2020; Kotz et al., 2022) and may also do so for inflation.

Second, our results are identified predominantly for food and headline inflation, while we find a limited response of other price aggregates to the climate measures we utilise. Electricity prices show some response to temperature with larger errors. Lesser data availability for this more detailed price aggregate as well as complex and heterogeneous electricity price-setting practices may contribute to these errors, but part of the obscurity of impacts here may also result from empirical misspecification. Indeed, the strong response of electricity demand to temperature (Auffhammer et al., 2017; Wenz et al., 2017) suggests that impacts on electricity prices are certainly plausible and that their identification may require more detailed analysis of either the heterogeneity across countries and seasons or the design of alternative climate measures. Moreover, as electricity supply is - at least in parts of the world – increasingly met with renewable sources, the price sensitivity to temperature may change, warranting further research. A detailed analysis of other price aggregates may be a fruitful avenue of future work, as well as the investigation of other important mechanisms such as the spill-over of climate impacts on inflation via trade (Kuhla et al., 2021) which may have important implications for commodity-intensive components in particular.

The estimated inflationary impacts on food and headline price aggregates from projected future warming have considerable implications for both price stability and wider societal welfare. Persistent additional upward pressures on annual food inflation from a changing climate across the world of magnitudes of 1-3 p.p.p.y. by 2035 (as demonstrated in Fig. 2 and Table 1) would place global incomes under pressure from rising prices and could impact inflation expectations, thereby requiring monetary policy to react. These impacts will be heterogenous across regions, with generally larger impacts in the global south. Heterogeneous impacts may be particularly challenging for economic union areas such as the EU where larger inflationary impacts from climate change in southern Europe may increase inflation differentials with implications for monetary policy. Moreover, this may exacerbate pre-existing welfare discrepancies which can fuel anti-EU sentiment (Kuhn et al., 2016). In addition to the impacts arising from average future warming, the chaotic nature of temperature anomalies implies short-term, more rapid prices rises from exceptionally hot summers such as in Europe in 2022 (Fig. 4). The increasing intensity of such hot extremes with climate change will amplify their impact. Such additional shocks to prices – happening at unpredictable intervals but with increasing intensity – would pose additional challenges to monetary policy, especially when occurring on top of persistently higher inflationary pressures from higher average temperatures. Importantly, these impacts from both average warming and extremes would increase considerably by 2060 (approximately doubling in comparison to 2035) if future emissions are not mitigated, thereby providing strong incentive for rapid mitigation of greenhouse gases to limit future warming and its inflationary impacts.

These estimated inflationary impacts from projected future warming do not explicitly model the potential role of adaptation, such as through technological progress, in limiting their extent. However, by accounting for the heterogenous response of economies to climate shocks dependent on baseline climatic conditions and levels of socio-economic development, these results implicitly account for adaptation that has actually occurred historically via either prolonged exposure to (and presumably normalisation of) certain climatic conditions, or technological adaptations which are related to socio-economic development. The evidence suggests that both forms of historical adaptation have been very limited, with larger impacts in hotter regions and equivalent impacts across higher- and lower-income countries (Fig. 1, Table 1). As such, we interpret our results as the impacts which are likely to occur in the absence of historically un-precedented future adaptation. Such future adaptation offers an opportunity to limit these impacts and its occurrence may increase in likelihood as awareness of climate change and its impact increase. For example, planned adoption of space cooling could limit heat stress impacts on labour productivity and crop switching could limit agricultural productivity losses, two major channels of impacts with potential relevance to inflation. The efficacy and opportunity costs of such practices remain largely unknown and therefore present an important avenue for further research on the scope to limit the inflationary impacts of a warming climate and intensifying heat extremes.

References

Abaidoo, R., Agyapong, E.K., 2022. Commodity price volatility, inflation uncertainty and political stability. Int. Rev. Econ. 1–31.

Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., Rogelj, J., others, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group14 I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Technical Summary.

Auffhammer, M., Baylis, P., Hausman, C.H., 2017. Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. Proc. Natl. Acad. Sci. 114, 1886–1891.

Auffhammer, M., Hsiang, S.M., Schlenker, W., Sobel, A., 2020. Using weather data and climate model output in economic analyses of climate change. Rev. Environ. Econ. Policy.

Bolton, P., Despres, M., Da Silva, L.A.P., Samama, F., Svartzman, R., others, 2020. The green swan. BIS Books.

Boneva, L., Ferrucci, G., Mongelli, F.P., 2021. To be or not to be "green": how can monetary policy react to climate change? ECB Occas. Pap.

Bressler, R.D., 2021. The mortality cost of carbon. Nat. Commun. 12, 1–12.

Burke, M., Davis, W.M., Diffenbaugh, N.S., 2018. Large potential reduction in economic damages under UN mitigation targets. Nature 557, 549–553.

Burke, M., Hsiang, S.M., Miguel, E., 2015. Global non-linear effect of temperature on economic production. Nature 527, 235–239.

Chu, A.C., Lai, C.-C., 2013. Money and the welfare cost of inflation in an R&D growth model. J. Money Credit Bank. 45, 233–249.

Ciccarelli, M., Kuik, F., Martinez Hernandez, C., n.d. The asymmetric effects of weather shocks on euro area prices. Forthcoming.

Cucchi, M., Weedon, G.P., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., Hersbach, H., Buontempo, C., 2020. WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. Earth Syst. Sci. Data 12, 2097–2120.

Damania, R., 2020. The economics of water scarcity and variability. Oxf. Rev. Econ. Policy 36, 24–44.

Dasgupta, S., van Maanen, N., Gosling, S.N., Piontek, F., Otto, C., Schleussner, C.-F., 2021. Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet Planet. Health 5, e455–e465.

de Lima, C.Z., Buzan, J.R., Moore, F.C., Baldos, U.L.C., Huber, M., Hertel, T.W., 2021. Heat stress on agricultural workers exacerbates crop impacts of climate change. Environ. Res. Lett. 16, 044020.

Dell, M., Jones, B.F., Olken, B.A., 2012. Temperature shocks and economic growth: Evidence from the last half century. Am. Econ. J. Macroecon. 4, 66–95.

Dotsey, M., Ireland, P., 1996. The welfare cost of inflation in general equilibrium. J. Monet. Econ. 37, 29–47.

Driscoll, J.C., Kraay, A.C., 1998. Consistent covariance matrix estimation with spatially dependent panel data. Rev. Econ. Stat. 80, 549–560.

Drudi, F., Moench, E., Holthausen, C., Weber, P.-F., Ferrucci, G., Setzer, R., Nino, V.D., Barbiero, F., Faccia, D., Breitenfellner, A., others, 2021. Climate change and monetary policy in the euro area.

Faccia, D., Parker, M., Stracca, L., 2021. Feeling the heat: extreme temperatures and price stability.

Gazdar, H., Mallah, H.B., 2013. Inflation and food security in Pakistan: Impact and coping strategies. IDS Bull. 44, 31–37.

George Gray Molina, María Montoya-Aguirre, and Eduardo Ortiz-Juarez, 2022. Addressing the cost-of-living crisis in developing countries: Poverty and vulnerability projections and policy responses. U. N. High-Level Polit. Forum Sustain. Dev. HLPF.

Guo, Y., Gasparrini, A., Armstrong, B.G., Tawatsupa, B., Tobias, A., Lavigne, E., Coelho, M. de S.Z.S., Pan, X., Kim, H., Hashizume, M., others, 2016. Temperature variability and mortality: a multi-country study. Environ. Health Perspect. 124, 1554–1559.

Kalkuhl, M., Wenz, L., 2020. The impact of climate conditions on economic production. Evidence from a global panel of regions. J. Environ. Econ. Manag. 103, 102360.

Klein Goldewijk, K., Beusen, A., Van Drecht, G., De Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Glob. Ecol. Biogeogr. 20, 73–86.

Kotz, M., Levermann, A., Wenz, L., 2022. The effect of rainfall changes on economic production. Nature 601, 223–227.

Kotz, M., Wenz, L., Stechemesser, A., Kalkuhl, M., Levermann, A., 2021. Day-to-day temperature variability reduces economic growth. Nat. Clim. Change 11, 319–325.

Kuhla, K., Willner, S.N., Otto, C., Wenz, L., Levermann, A., 2021. Future heat stress to reduce people's purchasing power. PloS One 16, e0251210.

Kuhn, T., Van Elsas, E., Hakhverdian, A., van der Brug, W., 2016. An ever wider gap in an ever closer union: Rising inequalities and euroscepticism in 12 West European democracies, 1975–2009. Socio-Econ. Rev. 14, 27–45.

Lagarde, C., 2022. Painting the bigger picture: keeping climate change on the agenda. ECB Blog.

Lange, S., 2019. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1. 0). Geosci. Model Dev. 12, 3055–3070.

Lenton, T.M., Dakos, V., Bathiany, S., Scheffer, M., 2017. Observed trends in the magnitude and persistence of monthly temperature variability. Sci. Rep. 7, 1–10.

Liang, X.-Z., Wu, Y., Chambers, R.G., Schmoldt, D.L., Gao, W., Liu, C., Liu, Y.-A., Sun, C., Kennedy, J.A., 2017. Determining climate effects on US total agricultural productivity. Proc. Natl. Acad. Sci. 114, E2285–E2292.

Moessner, R., 2022. Effects of Precipitation on Food Consumer Price Inflation.

Moore, F.C., Baldos, U., Hertel, T., Diaz, D., 2017a. New science of climate change impacts on agriculture implies higher social cost of carbon. Nat. Commun. 8, 1–9.

Moore, F.C., Baldos, U.L.C., Hertel, T., 2017b. Economic impacts of climate change on agriculture: a comparison of process-based and statistical yield models. Environ. Res. Lett. 12, 065008.

Moore, F.C., Diaz, D.B., 2015. Temperature impacts on economic growth warrant stringent mitigation policy. Nat. Clim. Change 5, 127–131.

Mukherjee, K., Ouattara, B., 2021. Climate and monetary policy: do temperature shocks lead to inflationary pressures? Clim. Change 167, 1–21.

Nord, M., Coleman-Jensen, A., Gregory, C., 2014. Prevalence of US food insecurity is related to changes in unemployment, inflation, and the price of food.

Osbat, C., Parker, M., Forthcoming. Global consumer price index dataset. Forthcoming.

Parker, M., 2018. The impact of disasters on inflation. Econ. Disasters Clim. Change 2, 21–48.

Previdi, M., Smith, K.L., Polvani, L.M., 2021. Arctic amplification of climate change: a review of underlying mechanisms. Environ. Res. Lett. 16, 093003.

Rode, A., Carleton, T., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Jina, A., Kopp, R.E., McCusker, K.E., others, 2021. Estimating a social cost of carbon for global energy consumption. Nature 598, 308–314.

Semenov, M.A., Porter, J., 1995. Climatic variability and the modelling of crop yields. Agric. For. Meteorol. 73, 265–283.

Song, X., Wang, S., Hu, Y., Yue, M., Zhang, T., Liu, Y., Tian, J., Shang, K., 2017. Impact of ambient temperature on morbidity and mortality: an overview of reviews. Sci. Total Environ. 586, 241–254.

van der Wiel, K., Bintanja, R., 2021. Contribution of climatic changes in mean and variability to monthly temperature and precipitation extremes. Commun. Earth Environ. 2, 1–11.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23, 1696–1718.

Vidal-Quadras Costa, I., Saez Moreno, M., Kuik, F., Osbat, C., n.d. Forecasting food inflation with climate and commodities data using a non linear model. forthcoming.

Wenz, L., Levermann, A., Auffhammer, M., 2017. North–south polarization of European electricity consumption under future warming. Proc. Natl. Acad. Sci. 114, E7910–E7918.

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Prasad, P.V., 2000. Temperature variability and the yield of annual crops. Agric. Ecosyst. Environ. 82, 159–167.

Annex

A.1 Supplementary figures

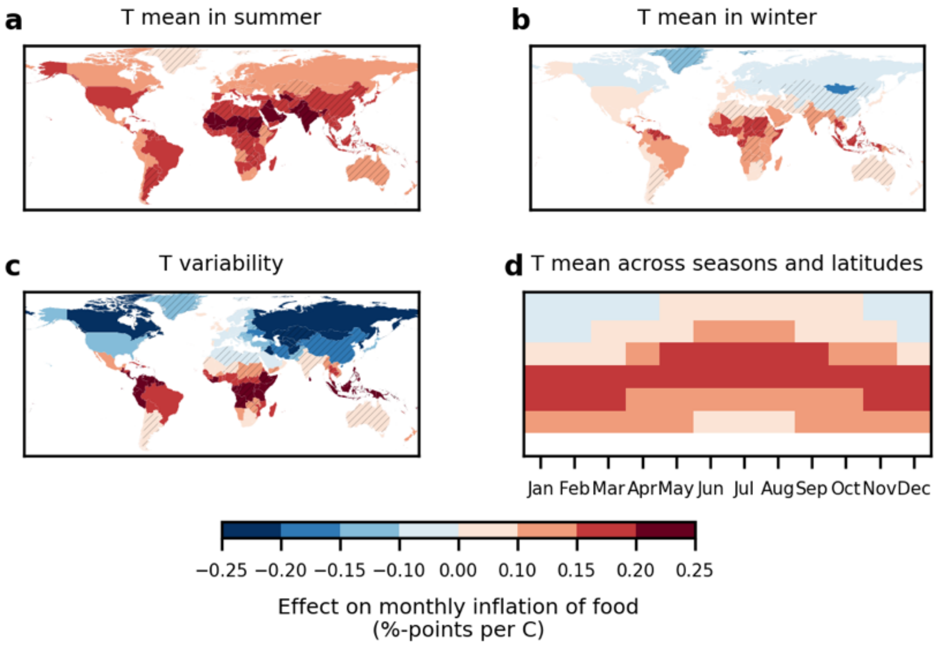


Figure S1. The historically observed non-linear response of inflation to temperature across regions and seasons. The cumulative response over 12 months of food inflation to a 1C increase in monthly mean temperature when occurring in either the hottest month of that countries year (a) or the coldest month of that countries year (b). The response to mean temperature increases in each separate month of the year, aggregated across latitudinal zones is shown in (d). The equivalent response of inflation to a 1C increase in daily temperature variability in any month of a given country (c). Estimates are extrapolated to regions without data on consumer price indices by evaluating the marginal effects estimated in Fig. 1 at the values of the moderating variable (either mean temperature or the magnitude of the seasonal temperature cycle) for each country. Countries in which these marginal effects have been extrapolated are shown hatched.

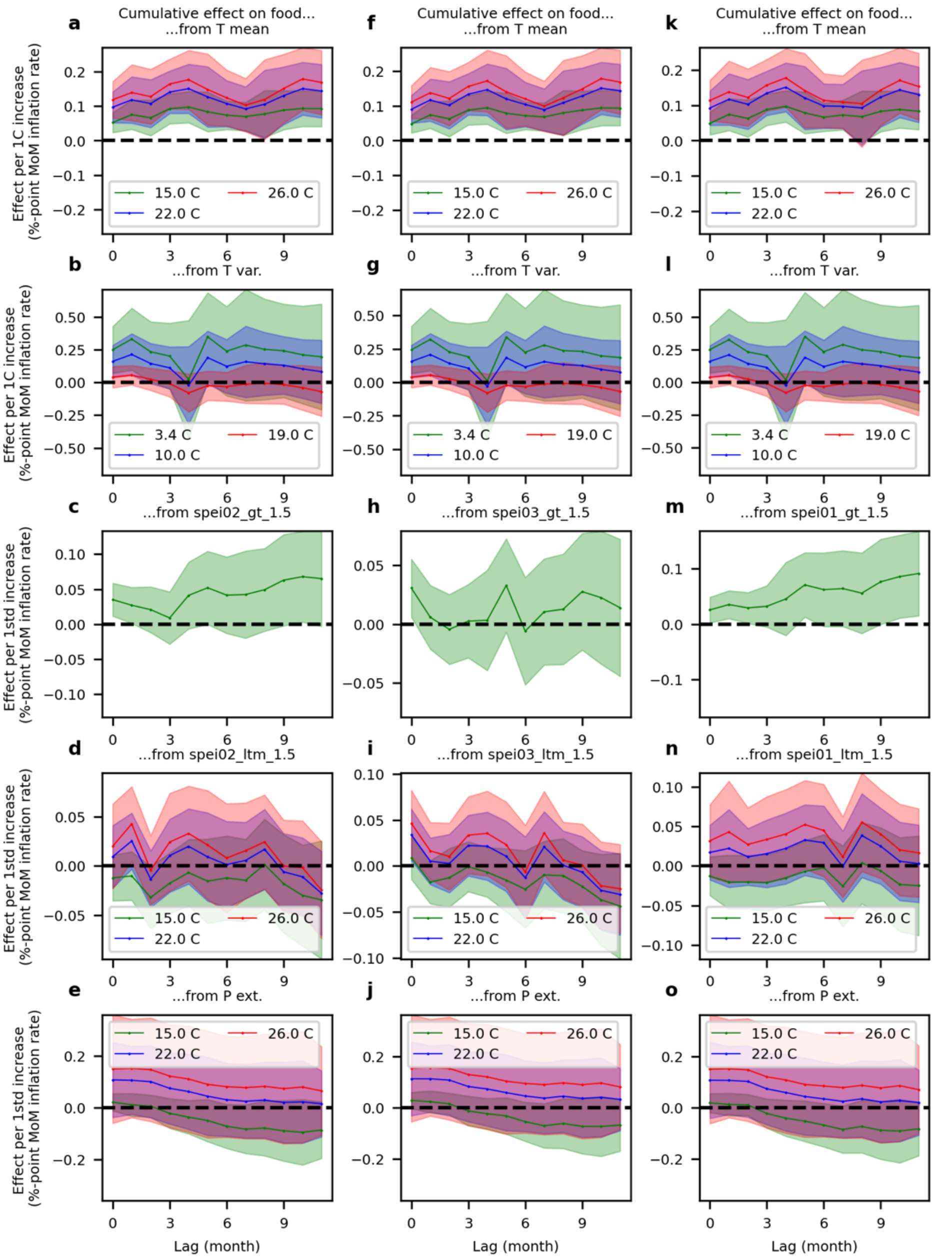


Figure S2. Precipitation impacts on inflation using SPEI at different timescales and impact thresholds. As Fig. 1 in the main manuscript but with alternative measures of excess wet and dry using SPEI at different timescales and impact thresholds. “spei0X_gt_Y” refers to a measure of national population exposure to SPEI values at a timescale of X months of greater than Y standard deviations, whereas “spei0X_ltm_Y” refers to the equivalent exposure at timescale of X months of less than minus Y standard deviations.

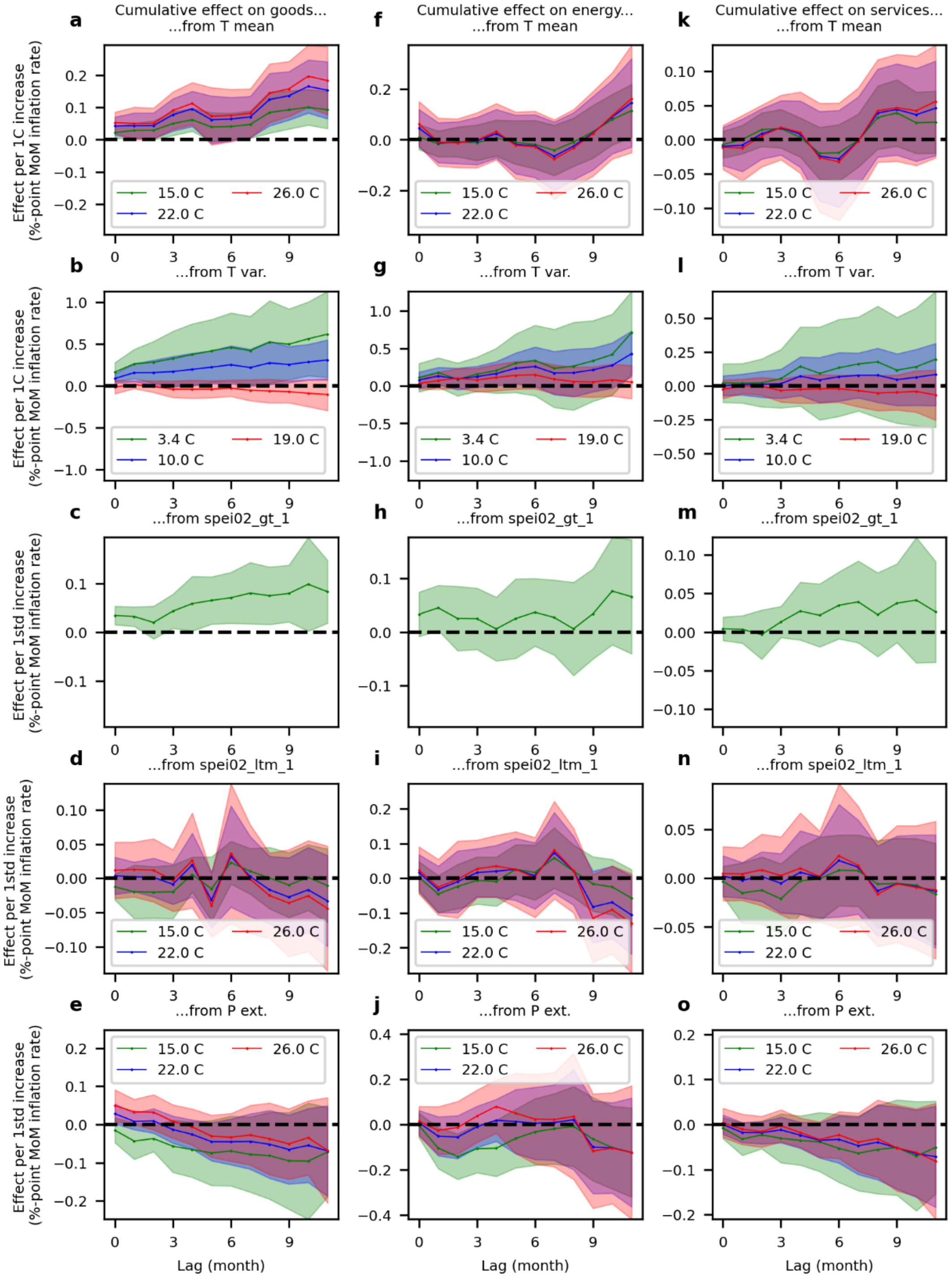


Figure S3. Historical impacts of climate variables on inflation in different price aggregates.

As Fig. 1 but showing results for special price aggregates (goods, energy and services). Note that food constitutes a considerable proportion of the goods price aggregate.

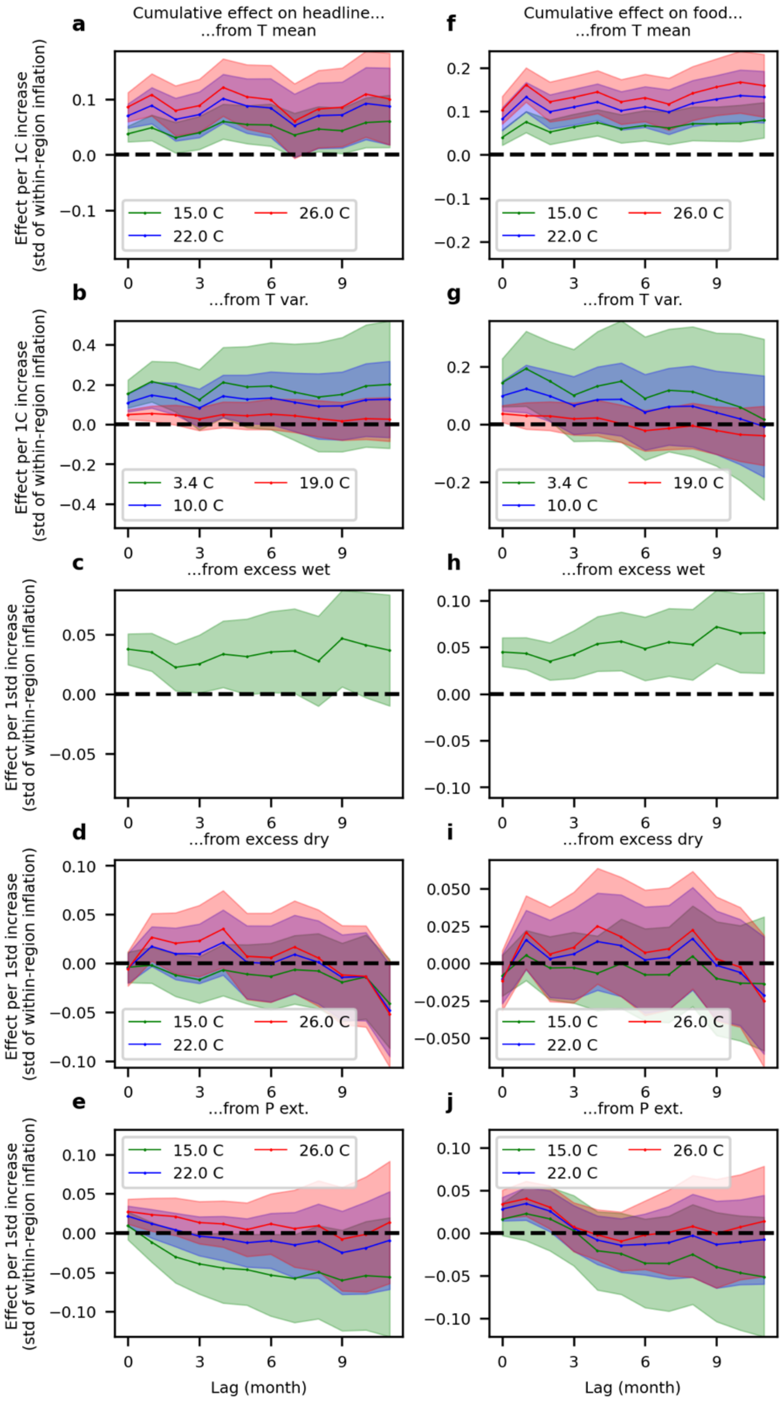


Figure S4. Historical impacts of climate variables on normalized inflation in headline and food price aggregates. As Fig. 1 but showing results having normalized monthly inflation rates by their within-country standard deviation. Note the y-axis units of within-region standard deviations.

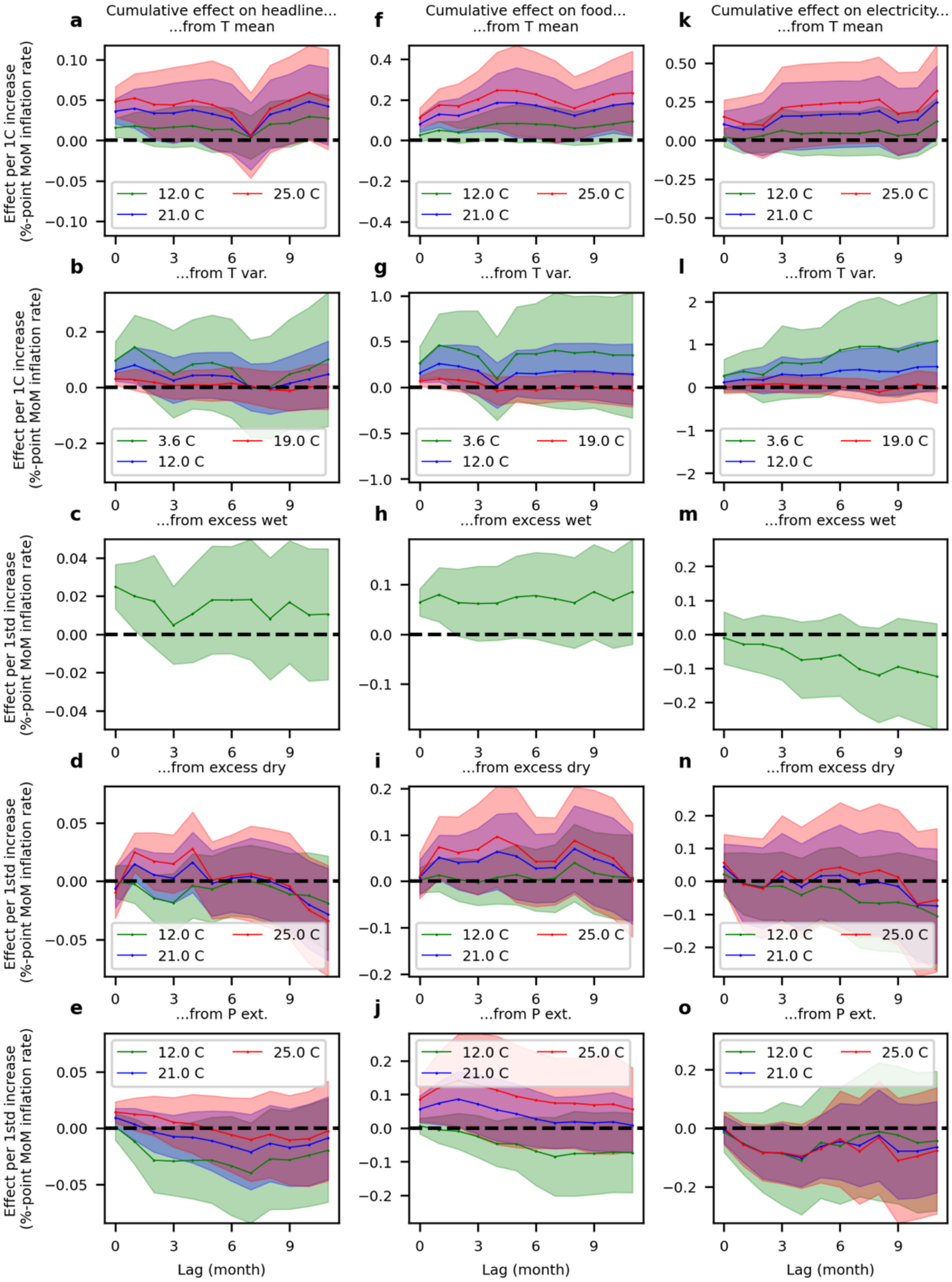


Figure S5. Historical impacts of climate variables on inflation using a dynamic lag specification and accounting for cross-sectionally correlated errors. As Fig. 1 but results for this alternative specification.

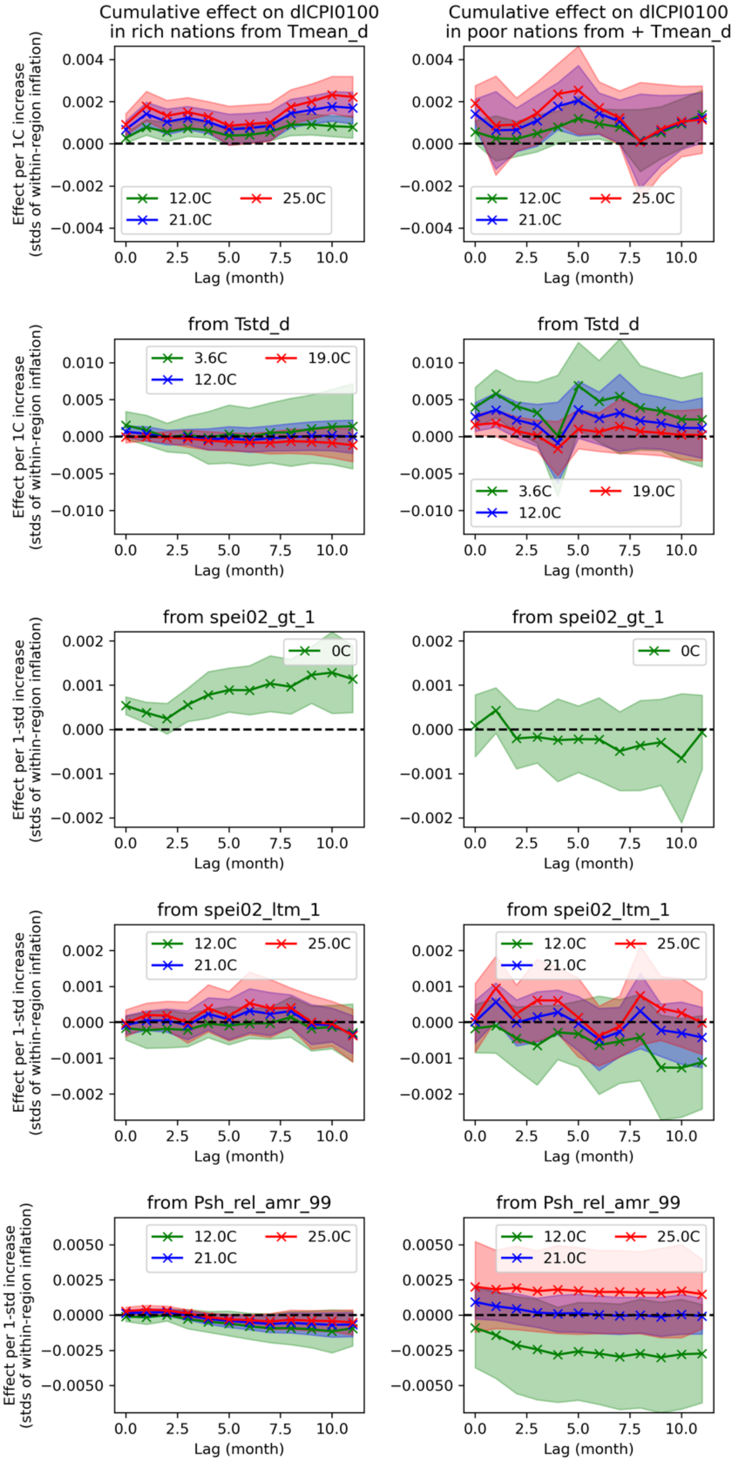


Figure S6. Historical impacts of climate variables on inflation accounting for heterogenous impacts across socio-economic conditions. As Fig. 1 but having estimated separately for above and below-median income countries.

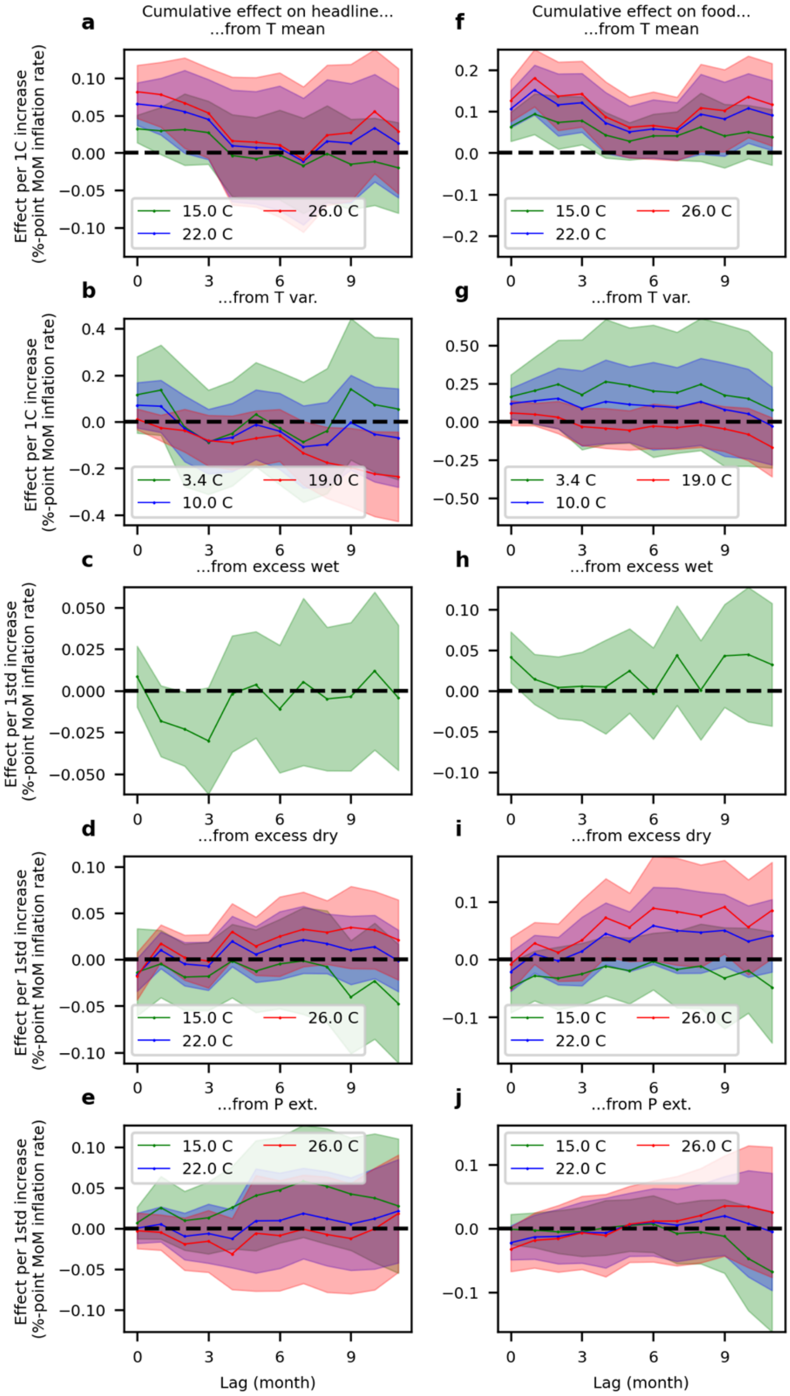


Figure S7. Historical impacts of climate variables on inflation using World Bank data on price aggregates. As Fig. 1 but using World Bank data, note the different methodological choices in constructing headline inflation in the World Bank and European Central Bank data used in our central specification (see methods).

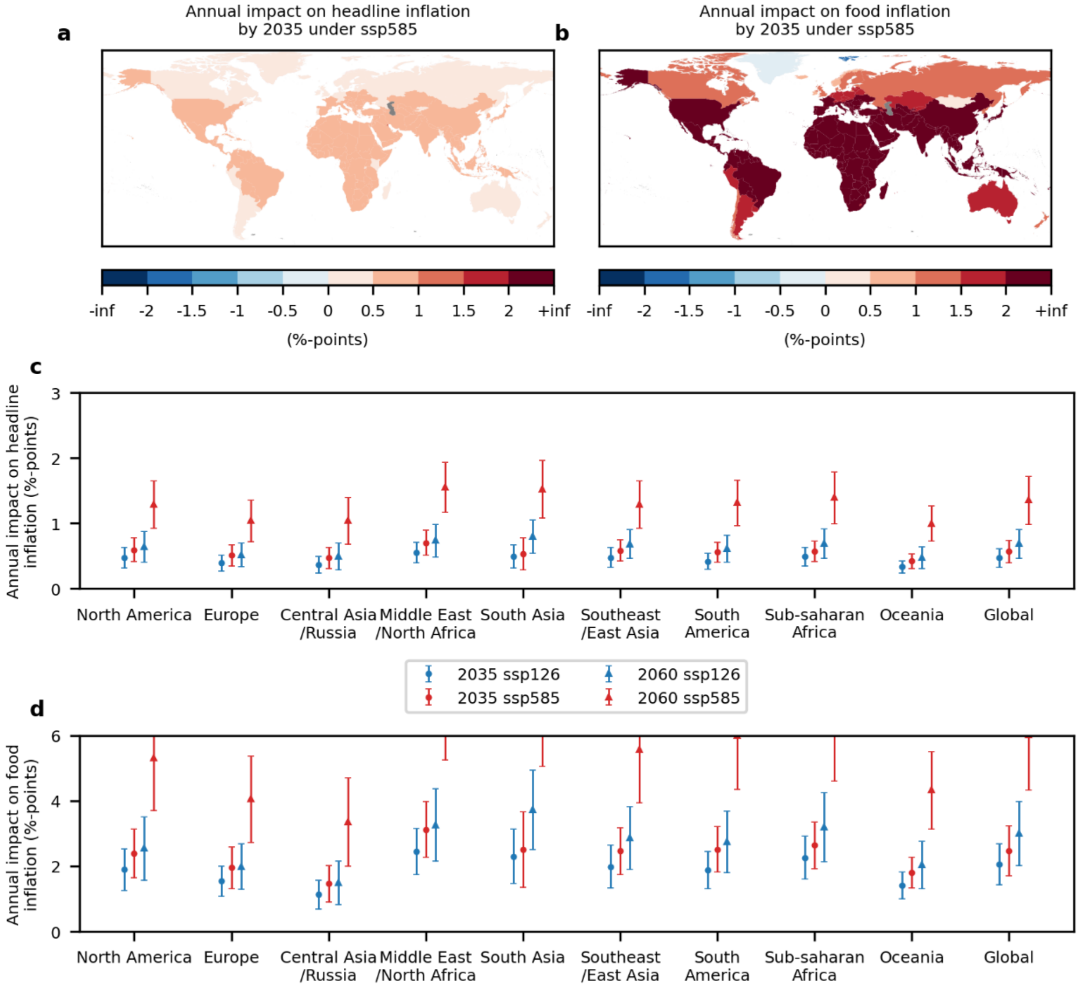


Figure S8. Estimated inflationary impacts from projected future warming using dynamic panel model. As Fig. 2 of the main manuscript but using the empirical specification shown in column 2 of Table 1.

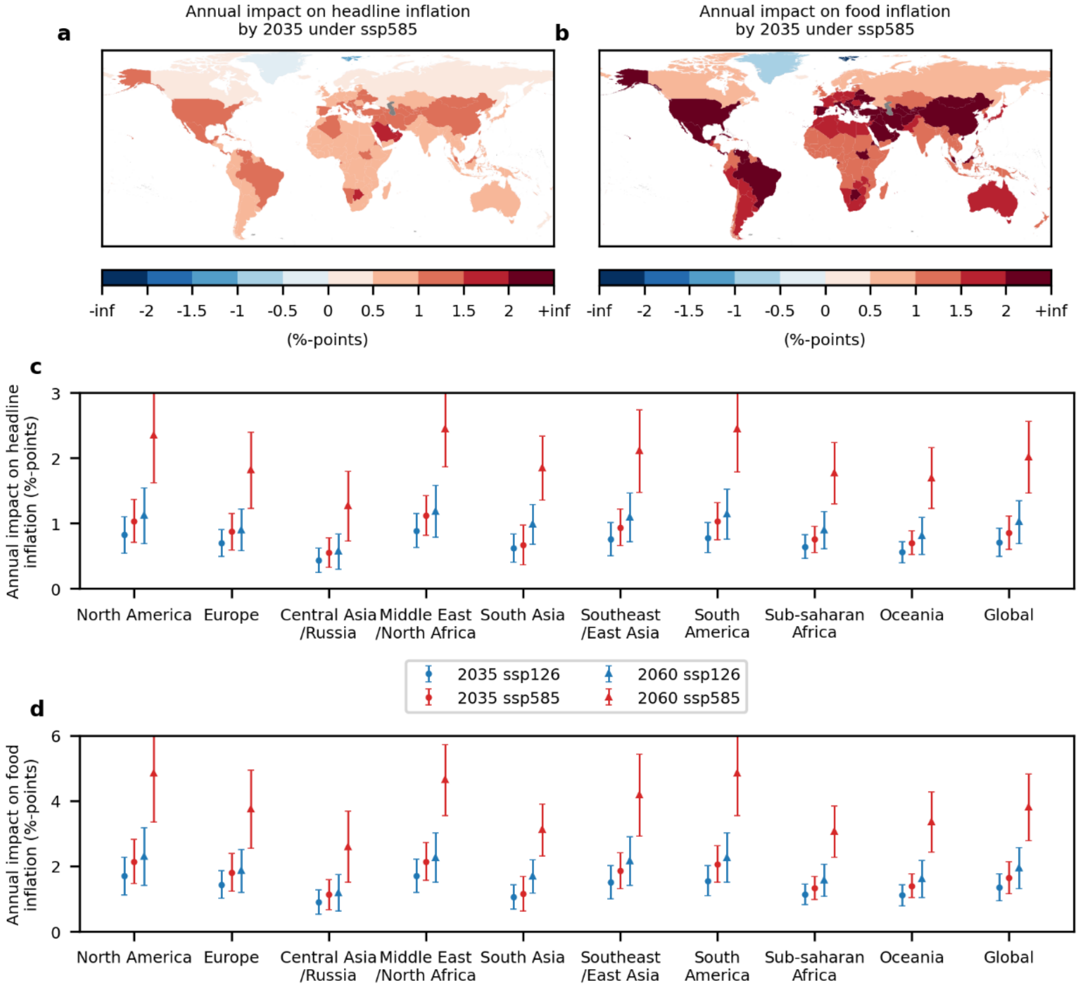


Figure S9. Estimated inflationary impacts from projected future warming accounting for the different responses between higher- and lower-income countries. As Fig. 2 of the main manuscript but using the empirical specification shown in column 4 of Table 1.

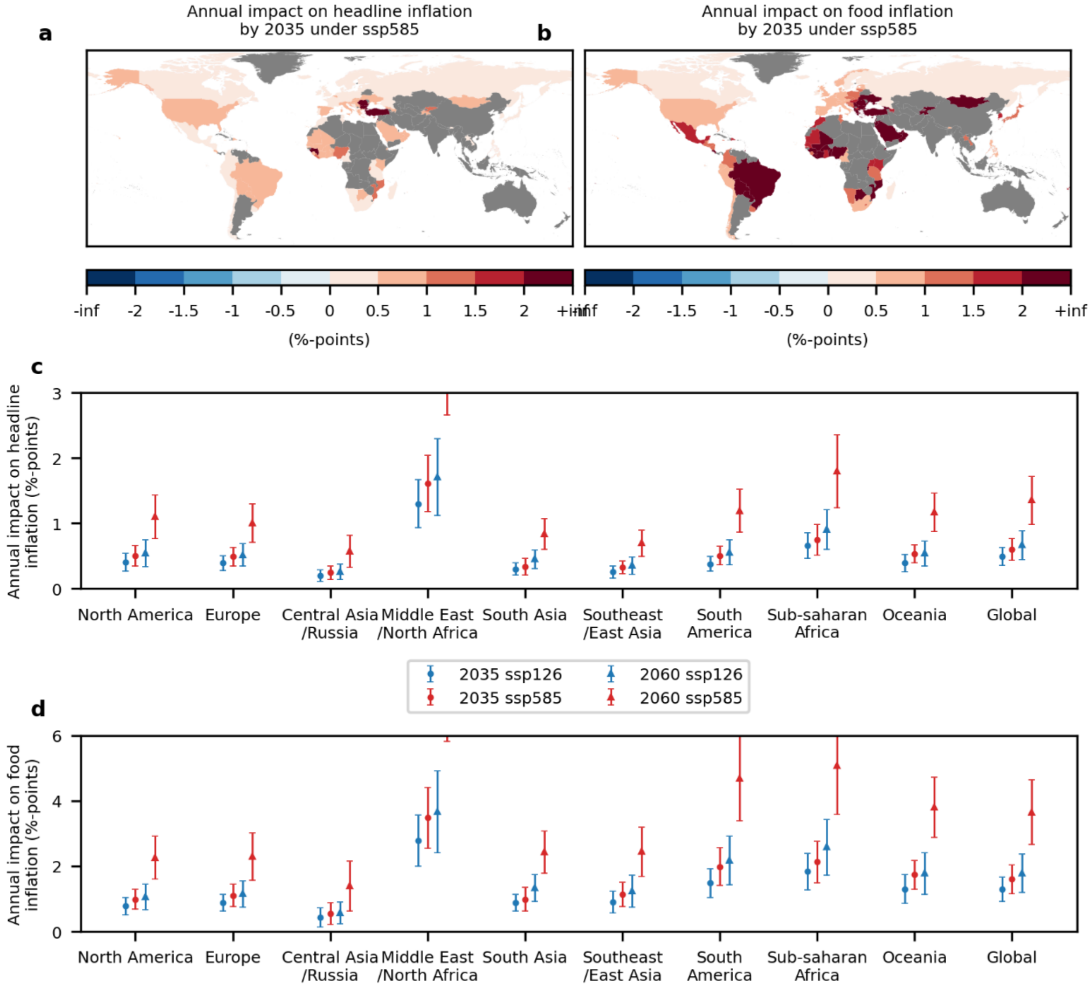


Figure S10. Estimated inflationary impacts from projected future warming accounting for the different responses of higher- and lower-income countries as well as baseline historical inflation volatility. As Fig. 2 of the main manuscript but using the empirical specification shown in column 5 of Table 1.

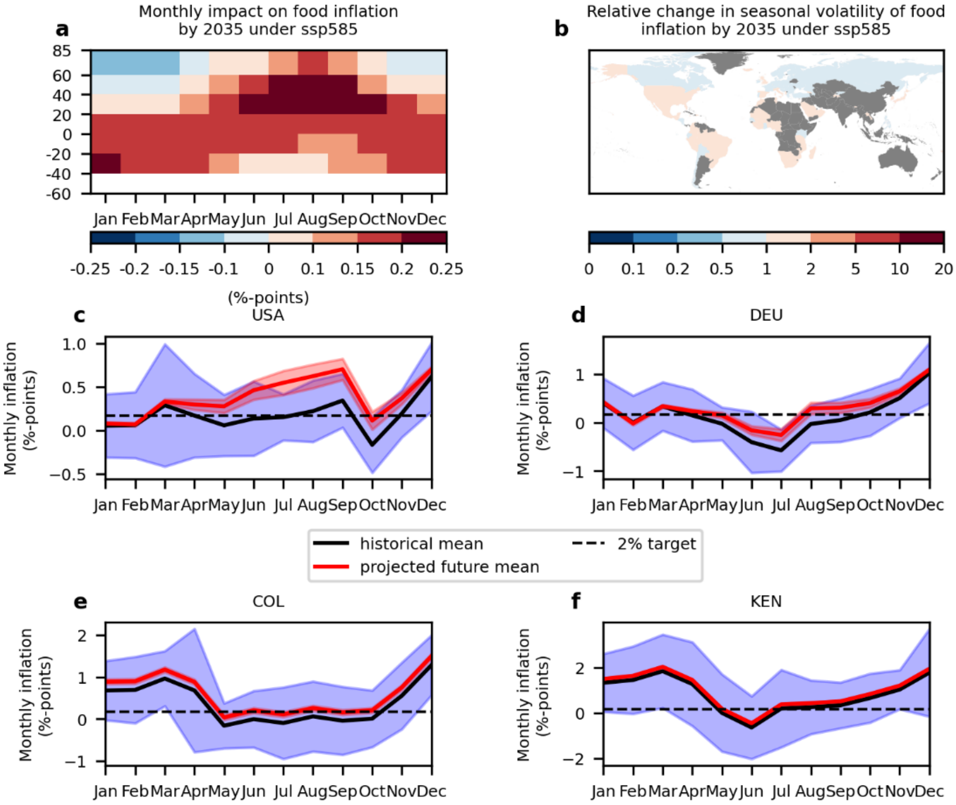


Figure S11. Seasonality of estimated impacts on food inflation from projected future warming using a dynamic panel specification. As Fig. 3 of the main manuscript but using the empirical specification shown in column 2 of Table 1.

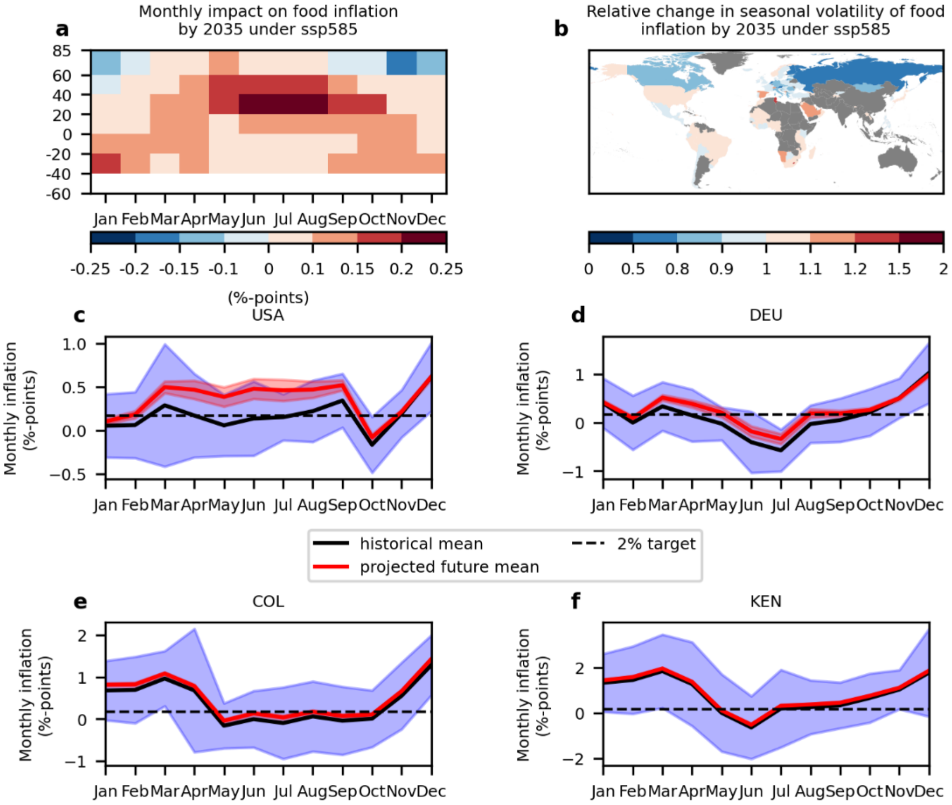


Figure S12. Seasonality of estimated impacts on food inflation from projected future warming accounting for the different response between higher- and lower-income countries. As Fig. 3 of the main manuscript but using the empirical specification shown in column 4 of Table 1.

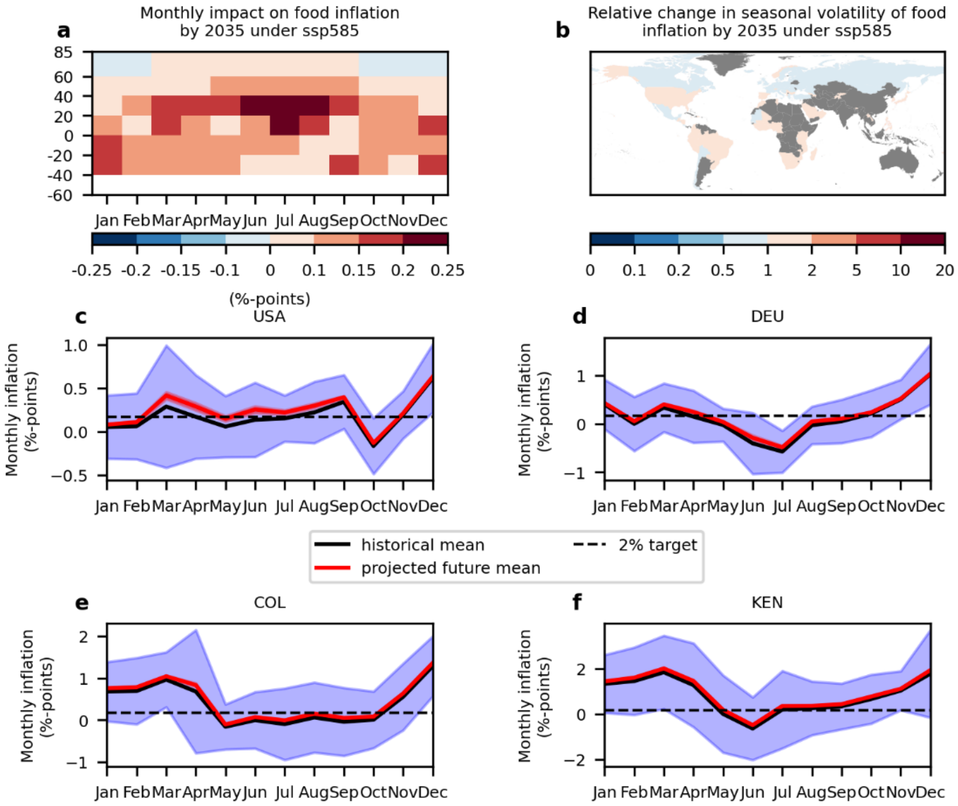


Figure S13. Seasonality of estimated impacts on food inflation from projected future warming accounting for the different response between higher- and lower-income countries and different historical baseline inflation volatilities. As Fig. 3 of the main manuscript but using the empirical specification shown in column 5 of Table 1.

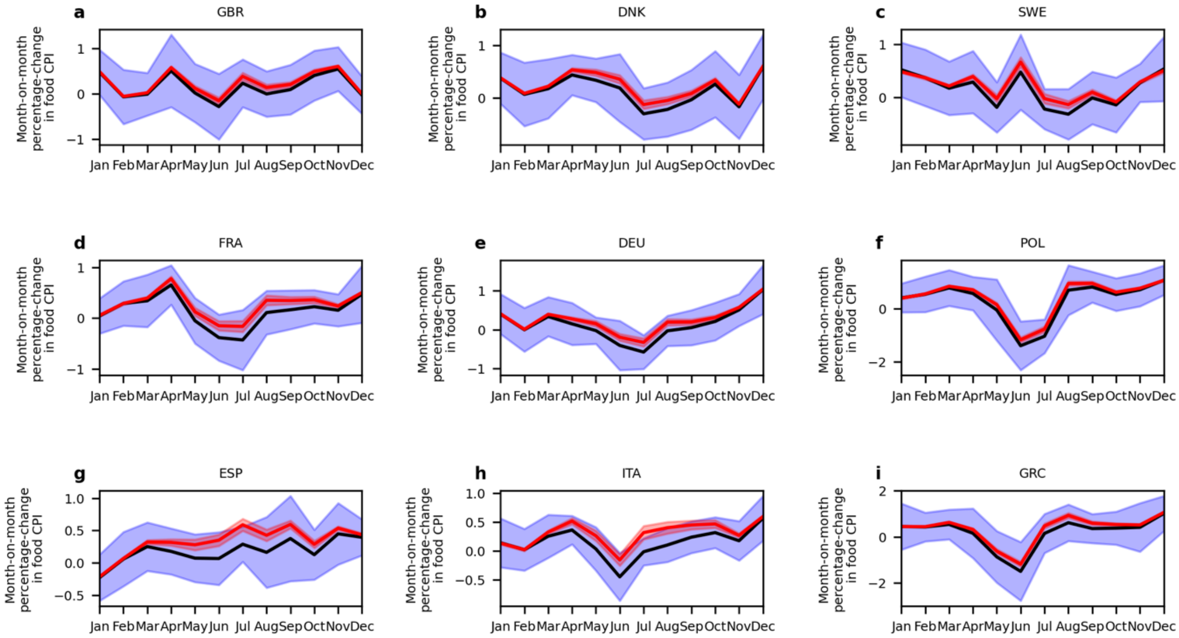


Figure S14. Seasonality of estimated impacts on food inflation from projected future warming for major European economies by 2035 under a high-emission scenario. As Fig. 3c-f but for a broader range of countries.

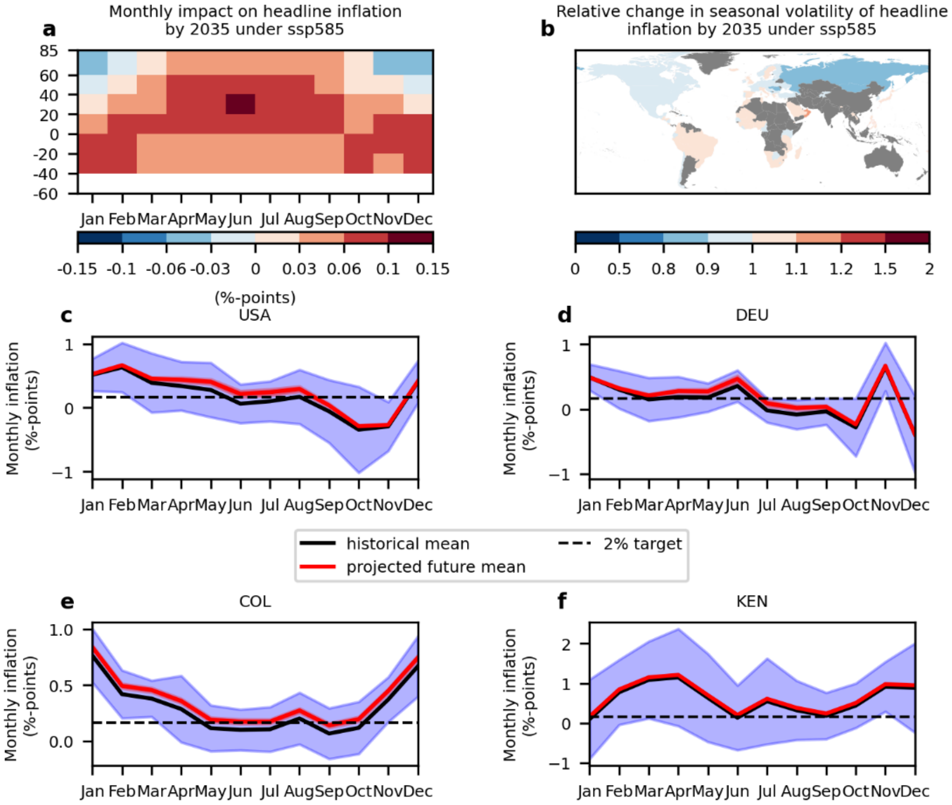


Figure S15. Seasonality of estimated impacts on headline inflation from projected future warming. As Fig. 3 of the main manuscript but for headline inflation.

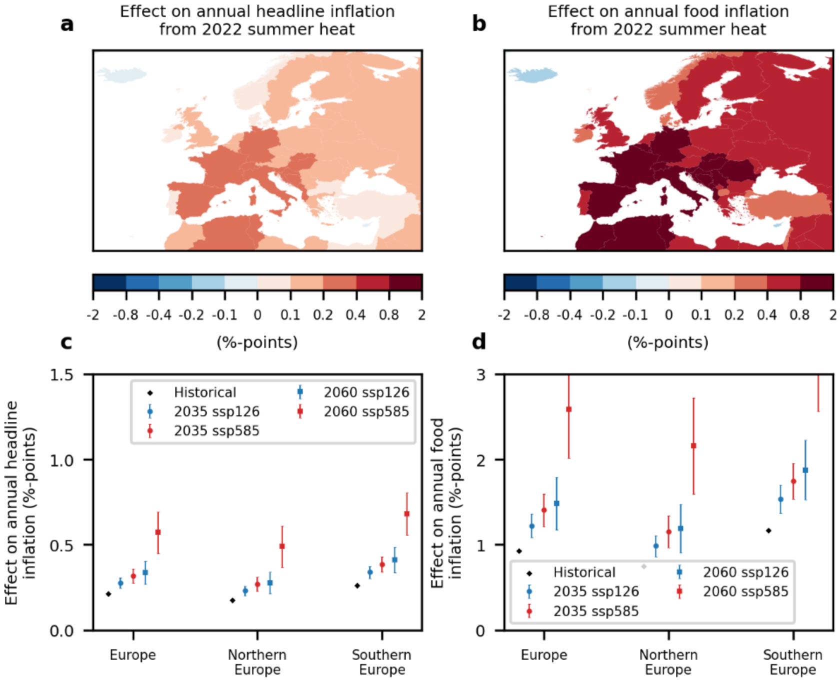


Figure S16. Estimated impacts of 2022 summer extreme heat in Europe on inflation, and the amplification of such impacts under projected future warming, using a dynamic panel specification. As Fig. 4 of the main manuscript but using the empirical specification shown in column 2 of Table 1.

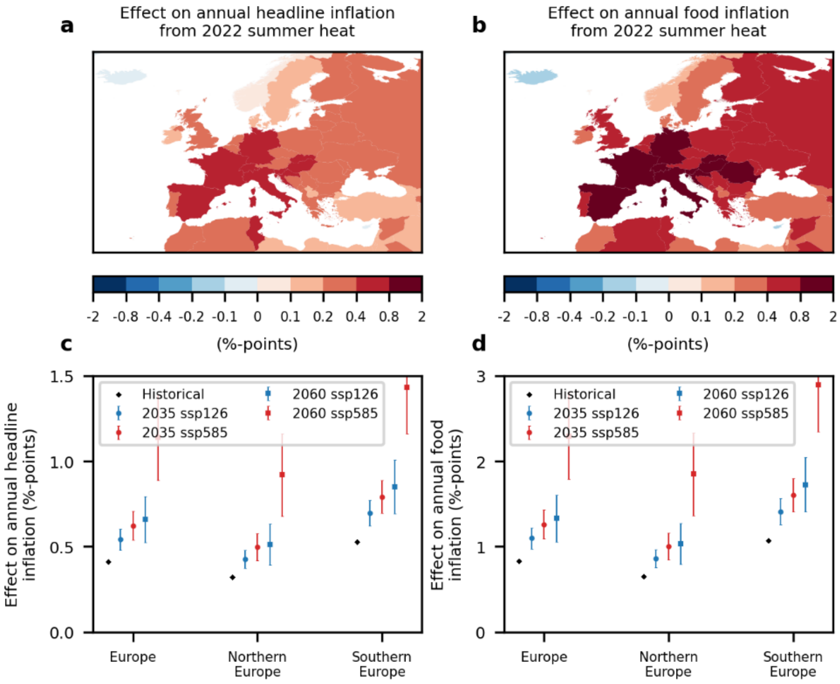


Figure S17. Estimated impacts of 2022 summer extreme heat in Europe on inflation, and the amplification of such impacts under projected future warming, accounting for the different response between higher- and lower-income countries. As Fig. 4 of the main manuscript but using the empirical specification shown in column 4 of Table 1.

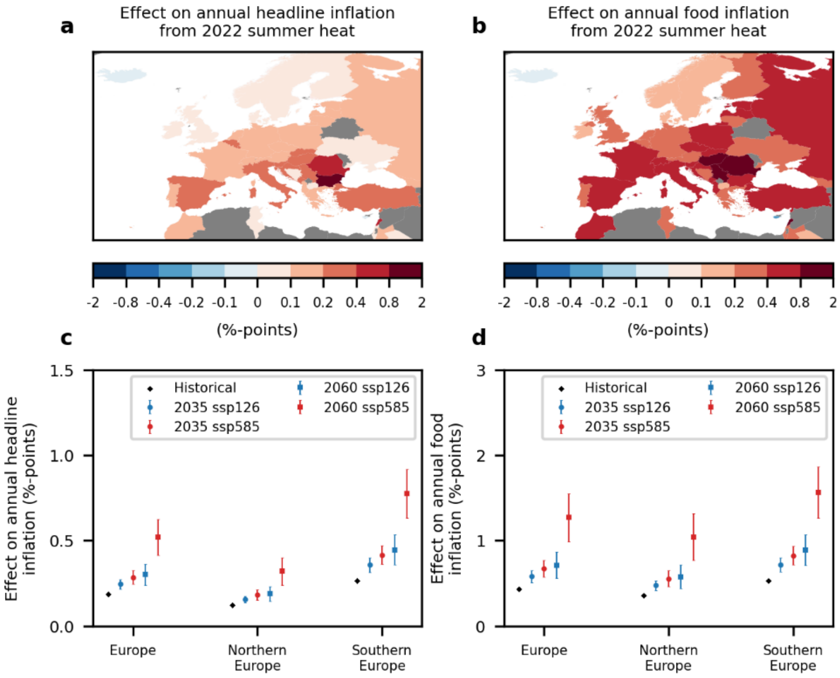


Figure S18. Estimated impacts of 2022 summer extreme heat in Europe on inflation, and the amplification of such impacts under projected future warming, accounting for the different response between higher- and lower-income countries and for different historical inflation volatilities. As Fig. 4 of the main manuscript but using the empirical specification shown in column 5 of Table 1.

Acknowledgements

We thank Chiara Osbat, Miles Parker, Mario Porqueddu and participants of an ECB-internal seminar for helpful comments and discussions. We acknowledge Potsdam Institute for Climate Impact Research for use of their high-performance computing facilities and data management services.
The views expressed in this paper are those of the authors and should not be reported as representing the views of the European Central Bank (ECB) or the Eurosystem.

Maximilian Kotz
Potsdam Institute for Climate Impact Research, Potsdam, Germany; Institute of Physics, Potsdam University, Potsdam, Germany; email: maxkotz@pik-potdsam.de

Friderike Kuik
European Central Bank, Frankfurt am Main, Germany; email: friderike.kuik@ecb.europa.eu

Eliza Lis
European Central Bank, Frankfurt am Main, Germany; email: eliza.lis@ecb.europa.eu

Christiane Nickel
European Central Bank, Frankfurt am Main, Germany; email: christiane.nickel@ecb.europa.eu

© European Central Bank, 2023

Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu

All rights reserved. Any reproduction, publication and reprint in the form of a different publication, whether printed or produced electronically, in whole or in part, is permitted only with the explicit written authorisation of the ECB or the authors.

This paper can be downloaded without charge from www.ecb.europa.eu, from the Social Science Research Network electronic library or from RePEc: Research Papers in Economics. Information on all of the papers published in the ECB Working Paper Series can be found on the ECB's website.

PDF ISBN 978-92-899-6084-7 ISSN 1725-2806 doi:10.2866/46035 QB-AR-23-058-EN-N