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EVIDENCE ON CROSS-COUNTRY RESPONSE HETEROGENEITY

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ABSTRACT

We use local projections to estimate the cross-country distribution of real GDP per capita growth impulse responses to global and idiosyncratic temperature shocks. Negative growth responses to global temperature at longer horizons are found for all Group of Seven countries while positive responses are found for seven of the nine poorest countries. Global temperature shocks have negative effects on growth for around half of the countries and seemingly anomalous positive effects for the other half. After controlling for latitude and average temperature, positive growth responses to global temperature shocks are more likely for countries that are poorer, have experienced slower growth, are less educated (lower high school attainment), less open to trade, and more authoritarian.

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1 Introduction

This paper studies how GDP responds to temperature change and how these responses vary across countries. We decompose a country's temperature into global (common) and idiosyncratic components, then use local projections [Jordà, 2005] to estimate the responses of real GDP per capita growth to each temperature component. The distribution of cross-country responses to both global and idiosyncratic temperature shocks displays heterogeneity in sign and in magnitude. The number of countries with negative growth responses to idiosyncratic temperature shocks exceed positive responses. The cross-country growth response to shocks to global temperature are more evenly split between positive and negative. In many cases, the responses of a given country to global and idiosyncratic temperature shocks go in opposite directions. These differences highlight the importance of including both sources of temperature fluctuations in order to isolate the broader effects of global temperature change.

Much of the related literature, discussed below, employs panel regression techniques that imposes extensive homogeneity restrictions across countries. These studies either find uniformly negative effects of higher temperature on growth for all countries, or negative effects only for poor countries with inconclusive results for the rich. This paper departs from the literature along two main dimensions. First, in contrast to panel regression, we use local projections, which imposes few restrictions and allows for complete cross-country response heterogeneity. The second departure lies in the decomposition of country-level temperature into orthogonal global and idiosyncratic components, whereas much of the previous research regressed country i real GDP per capita growth on a measure of country i specific temperature. Our global and idiosyncratic components are similar in spirit to a permanent and transitory decomposition. The global component, reflecting global warming, is trending upward and shocks to it are permanent. The idiosyncratic component, on the other hand, is transitory by construction.

The idiosyncratic component is similar to the regressand in panel regressions with time-fixed effects. Global temperature is more systematic and less noisy than country temperature, since it is a cross-country average. If each country is a small open economy, not only would that country's own temperature matter for growth, but temperature should work indirectly through its effect on the rest-of-world then circling back to the country in question via trade and financial linkages. These external, spill-over effects can be captured by global temperature shocks.

The temperature decomposition is also useful because global temperature is conceptually closer to climate change, which is a global phenomenon. We find impulse responses of rich country real GDP per capita growth to global temperature variation tend to be negative. At longer horizons, all of the Group of Seven (G-7) countries have negative responses (although Canada's is not significant), whereas many of the responses by poor countries tend to be positive.

To study the determinants of cross-country response variation, we regress the local projection impulse response coefficients on various country characteristics. This methodology draws on research strategies used in finance (e.g., Lustig and Richmond [2020] who regress the exchange rate's dollar-factor 'beta' on gravity variables). Note that there is no 'generated regressor' problem in this cross-sectional analysis because the estimated response coefficients are the dependent variable. We find the country-level attributes have little explanatory power for the idiosyncratic responses. Country-level characteristics do a better job of explaining the impact from the global component. At longer horizons (4 and 5 years), positive growth responses to global temperature shocks, which would appear to be anomalous, are more likely for countries that are poorer, have experienced slower growth, are less educated (lower high school attainment), less open to trade, and more authoritarian. Surprisingly, the average agricultural share in the economy is never significant.

A central motivation for this project is to shed light on limited and conflicting conclusions in the literature regarding impact heterogeneity of temperature variation on real GDP per capita growth. Depending on the particular study, the empirical literature that employs panel regressions find either an inverse relationship between temperature and GDP for all countries, or an inverse relationship that holds only for poor countries. A path-breaking study in this literature is Dell et al. [2012] who use international data in estimation with country and time-fixed effects. An important motive for their panel regression approach was to use country fixed effects to control for omitted-variables bias that was present in an earlier generation of studies of cross-sectional regressions of time-averaged GDP on temperature.[1] Dell et al. [2012] reports that increased temperature lowers GDP per capita growth, but only for poor countries. Leta and Tol [2019] and Henseler and Schumacher [2019] report similar results for total factor productivity growth. Burke et al. [2015], on the other hand, find increased temperature to have a negative effect on GDP growth but do not find differential impacts between rich and poor countries. Bansal and Ochoa [2011] find increasing global temperature lowers GDP growth of all countries with larger effects on low latitude countries.[2]

Informed by the extant literature, our prior beliefs were that the time-series variation would reveal a distribution of negative local projection coefficients with the far left tail populated primarily by poor, low latitude countries. It was surprising for us to estimate the direction of growth responses to be more evenly split between positive and negative and to find that many of the richer countries fall on the negative side of the distribution. Our empirical approach relaxes homogeneity restrictions which is prevalent in the existing literature. As a result, we unmask

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[1] The most prominent candidate omitted variables may be institutional quality, which is controlled for by the country fixed effect in panel regressions. Studies by Acemoglu et al. [2002], Easterly and Levine [2003], and Rodrik et al. [2004] argue institutions are main drivers of long-run growth outcomes.

[2] The panel regression approach to study the economic effects of climate was introduced by Deschênes and Greenstone [2007], who estimated the effect of temperature on agricultural profits in the United States. Also, focusing on the United States, Colacito et al. [2019] reports higher summer temperatures are damaging to output growth in southern states and the negative impacts are by geography, not income. Hsiang et al. [2017], who examines growth in county-level income, similarly finds income is negatively impacted by temperature in the south and southwest, and increases in the north.

significant heterogeneity.

Some broader implications follow from this project. First, the pattern of cross-country response heterogeneity can supplement the ethical arguments presented by Stern [2008] to incentivize rich countries to invest in abatement strategies. The evidence that rich countries are directly economically damaged by warming should naturally incentive them to invest in climate mitigation.[3] Furthermore, if environmental policy is largely informed by observing past relationships –and we show that the sign of these responses are not uniform across countries – our results identify an additional reason why forming a global consensus on future abatement strategies is difficult. Our results can also inform refinements to damage function specifications in integrated assessment models (IAM) that compute welfare costs and evaluate the social cost of carbon. Since much of the empirical literature finds higher temperatures to be more economically damaging to poorer and hotter regions, regional IAMs, informed by such empirical damage estimates produce similar regional damage projections.[4] The geographical variation provided by our country-specific assessments to the knowledge base can provide more detailed specifications of IAM damage functions. However, our findings show that growth in many countries, and many poor countries, respond positively to historical global temperature change. We believe these findings are robust given the historical record but acknowledge that these historical relationships between growth and temperature might change in the future following several degrees (Celsius) of additional warming due to 'tipping points' or adaptation.[5]

The remainder of the paper is organized as follows. Section 2 describes the data. Section 3 discusses substantive ways our analysis departs from panel regressions. The local projection analysis is reported in Section 4. Section 5 undertakes a cross-sectional analysis to understand the country-level attributes that, in part, account for the results. Section 6 concludes.

2 Data

Our empirical analysis explores the responses of real GDP per capita growth from temperature variation. In this section we first describe the sources and construction of our economic and temperature variation. Section 2.2 then describes how we decompose country-level temperature into global and idiosyncratic temperature components.

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[3] In the absence of a global coordinated effort, Stern [2008] appeals to two ethical considerations to get the rich, industrialized countries to shoulder disproportionate costs of future abatement. First, industrialized countries are responsible for most of the current stock of greenhouse gasses and have gotten rich by generating those emissions. Second, poor countries are just beginning to overcome poverty through rapid growth and should not be forced to slow.

[4] DICE, FUND, and PAGE are prominent IAMs that serve as the main policy models employed by the U.S. Environmental Protection Agency. Regional IAMS have been developed by Hassler and Krusell [2012], Nordhaus and Yang [1996], Tol [2019], and Ricke et al. [2018], amongst others.

[5] See Barreca et al. [2016], Kim et al. [2022], and Gandhi et al. [2022] for examples of adaptation to weather related phenomenon.

2.1 Data Sources

Real GDP per capita is from the World Bank's, *World Development Indicators*. These data are valued in constant 2010 United States dollars and have a maximal span from 1960-2017. The main empirical analysis uses only those 137 countries that have at least 30 consecutive years of observations.[6] In the analysis of Section 5, we also use the World Bank's, *World Development Indicators* to represent country characteristics.

Our temperature observations are population-weighted by year and country. The source is *Terrestrial Precipitation: 1900-2017 Gridded Monthly Time Series (V 5.01)* Matsuura and Willmott [2018]. This is a monthly dataset estimated from weather station records and interpolated to a 0.5-degree by 0.5-degree latitude/longitude grid. We aggregate the monthly data to annual observations by node. We overlay the temperature data with population data in 2000 from the *Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11* [Center for International Earth Science Information Network, 2018]. The data provides population counts at a 2.5 minute by 2.5 minute latitude/longitude grid. We use the population weights to obtain population-weighted temperatures by country and year, which is the standard approach in the literature (Kahn et al. 2019 and Dell et al. 2012).[7]

The temperature data is gridded and is interpolated among several ground stations. If we had consistent temperature measurement, temperature would be plausibly exogenous to any individual country's GDP. However, it has been pointed out that potential endogeneity arises if the underlying ground station temperature availability is dependent upon real GDP per capita growth (see Schultz and Mankin [2019] on the relation of civil conflict and discontinuity of weather station temperature readings). To address potential endogeneity concerns, we show in Appendix B that real GDP per capita growth is uncorrelated with weather station availability, thus mitigating these concerns. Going forward, we assume temperature is exogenous.

2.2 Temperature

Let country j temperature in year t be $\tau_{j,t}$. We decompose each $\tau_{j,t}$ into a common global component and a country-specific idiosyncratic component. This allows partial separation of geographically concentrated temperature variation and temperature change shared across countries.

Global temperature G_t, is the cross-sectional average of $\tau_{j,t}$ across the N countries,

$$G_t = \frac{1}{N}\sum_{j=1}^{N}\tau_{j,t}.$$

Idiosyncratic temperature $I_{j,t}$, is country temperature not explained by the global temperature.

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[6] The full list of countries and the available sample time period for each country are listed in Appendix A.

[7] We do not consider precipitation since earlier empirical work finds little or no effect of precipitation on income growth at the annual frequency.

It is measured as the residual from regressing country temperature $\tau_{j,t}$ on global temperature G_t,

$$I_{j,t} = \tau_{j,t} - \delta_j G_t - \alpha_j, \tag{1}$$

where α_j is the country intercept and δ_j is the slope coefficient on global temperature, G_t. By construction, the idiosyncratic component is stationary.

Figure 1 plots annual global temperature from 1900-2017. It is reasonably stable from 1900 to 1980. After 1980, an upward trend is visually obvious, rising by about 1^oC over 40 years. We describe how trending global temperature is dealt with econometrically in Section 3.2 below.

Figure 1: Cross-Sectional Average of Population-Weighted Country Annual Temperature

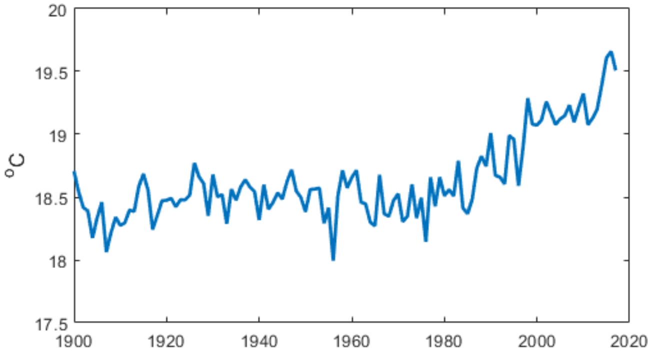
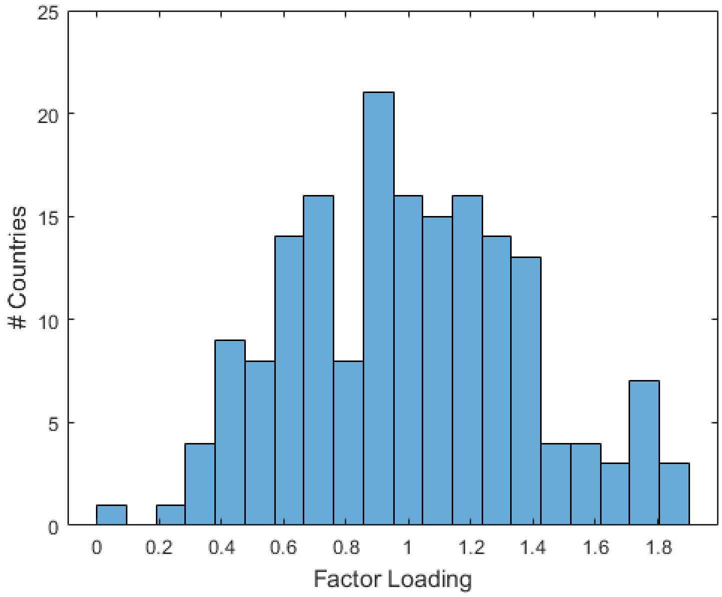


Figure 2 displays a histogram of the global temperature factor loadings (the δ_j) from the country-specific regressions in equation 1. The coefficients on all factor loadings are positive, meaning country-level temperatures all vary directly with global temperature. The distribution is centered around $\delta_j = 1$; by construction, country temperature varies one to one with global temperature on average. However, the dispersion of the estimates highlights that some country's actual temperature are more (less) impacted by global temperature changes.

Figure 2: Global Slope Coefficients (δ) from Equation (1)



3 Departures from Panel Regression

The related literature widely adopts panel regression estimation procedures with time-fixed effects to investigate the relationship between temperature changes and real GDP per capita growth (hereafter, *growth*).[8] Two features of panel regression with time-fixed effects obscure the relationship between temperature and growth. The first is the manner in which time-fixed effects removes the global component from growth and temperature, thus resulting in a regression of coarsely constructed idiosyncratic growth on idiosyncratic temperature variation. The effects of actual country-level and global temperature variation on growth are not observed. The second feature is the extensive homogeneity restrictions imposed on the slope coefficient of interest. While an objective of panel regression is to exploit cross-sectional variation to shrink standard errors, the imposition of extensive homogeneity should be imposed only when such restrictions are not rejected by the data. Section 3.2 shows they are rejected.

3.1 Time Fixed Effects

To illustrate the two points raised above, let $y_{j,t}$ be log real GDP per capita of country $j = 1, \ldots, N$ in time t. Without loss of generality, we abstract from time-invariant country-fixed

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[8] Kahn et al. [2019] is an exception, who estimate panel autoregressive-distributed lag models. They also find negative GDP growth impacts of temperature but no differences between rich and poor.

effects. Consider the panel regression of growth, $\Delta y_{j,t} = y_{j,t} - y_{j,t-1}$, on the country's annual temperature, $\tau_{j,t}$, with time fixed effects, θ_t,

$$\Delta y_{j,t} = \theta_t + \beta \tau_{j,t} + \epsilon_{j,t}. \tag{2}$$

Taking the cross-sectional average of equation (2) gives

$$\frac{1}{N}\sum_{j=1}^{N} \Delta y_{j,t} = \theta_t + \beta \frac{1}{N}\sum_{j=1}^{N} \tau_{j,t} + \frac{1}{N}\sum_{j=1}^{N} \epsilon_{j,t}. \tag{3}$$

Subtracting equation (3) from equation (2) eliminates the time-fixed effect giving,

$$\Delta y_{j,t} - \frac{1}{N}\sum_{j=1}^{N} \Delta y_{j,t} = \beta \left(\tau_{j,t} - \frac{1}{N}\sum_{j=1}^{N} \tau_{j,t} \right) + \left(\epsilon_{j,t} - \frac{1}{N}\sum_{j=1}^{N} \epsilon_{j,t} \right). \tag{4}$$

The variables in equation (4) are not growth and temperature, but are deviations of growth and temperature from their global averages. They are coarsely constructed idiosyncratic components of growth and temperature. Estimating the panel regression with time-fixed effects, equation (2), is equivalent to running stacked least squares on equation (4). The coefficient of interest β, does not measure the growth response to variations in the country's temperature. It measures the relative (to the world) growth response to relative (to the world) variations in temperature. If the panel estimate of β is negative, we can infer a country's growth is lower than average when it's temperature is hotter than average, but we cannot infer that global warming lowers growth.

3.2 Rejecting Extensive Homogeneity Restrictions with Local Projection at Horizon Zero

The literature has allowed modest amounts of heterogeneity on the slope for broad classes of countries (e.g., above and below median income) with dummy variable interactions. If one's interest is to study individual country responses, constrained (pooled) estimation should not proceed if the homogeneity restrictions are rejected. As a precursor to our main empirical work, we test, and reject, the extensive (i.e., across large numbers of countries) homogeneity restrictions that might typically be imposed in panel regressions.

Consider the regression of real GDP per capita growth on the global (G_t) and idiosyncratic (I_t) temperature factors. This is a local projection at horizon zero.

$$100\Delta y_{j,t} = \beta_j^G G_t + \beta_j^I I_{j,t} + x_{j,t}' \gamma_j + \epsilon_{j,t}, \tag{5}$$

where $x_{j,t}'\gamma_j = \sum_{k=1}^{4} \delta_{j,k} \Delta y_{j,t-k} + \sum_{k=1}^{2} \beta_{j,t-k}^G G_{t-k} + \sum_{k=1}^{2} \beta_{j,t-k}^I I_{j,t-k} + c_j$ are the regression constant and four lags of annual real GDP per capita growth, two lags of both global and idiosyncratic temperature components, included as controls. The timing of the variables conforms to those used in Dell et al. [2012].

Because the two temperature components are derived from country temperature, the same information is employed whether the regression includes only country temperature ($\tau_{j,t}$), country and global temperature ($\tau_{j,t}, G_t$), country and idiosyncratic temperature ($\tau_{j,t}, I_{j,t}$), or as in equation (5). Employing G_t and $I_{j,t}$ as in equation (5) permits the most straightforward identification of effects from the different components, except we do not identify the global temperature factor loading δ_j separately from the GDP response.

Note also that global temperature, which appears to be nonstationary, enters in levels. We specify the regression this way to get the most direct relationship between temperature and growth. The specification is justified by West [1988], who established asymptotic normality of the least squares estimator of β when G_t is nonstationary and when it is the only nonstationary variable in the regression. West's analysis was extended by Park and Phillips [1988] who established asymptotic normality of the least squares estimator of β when both current and lagged G_t are included, provided that G_t is exogenous, which we assume.

To test the homogeneity restrictions, we first estimate equation (5) separately for each country. Then, we sort countries into two groups: those whose $\hat{\beta}$s are positive and those whose are negative. Call them groups P (for positive) and N (for negative), respectively. Next, jointly estimate with all countries but constrain these slopes to be identical within group P and to be identical within group N. Call these slopes β_p and β_n, respectively. Then the Wald test of the hypothesis $\beta_p = \beta_n$ is χ^2_1 under the null. We do this for both slopes on global and idiosyncratic temperature. Apart from the slope on the contemporaneous temperature, all other coefficients are allowed to vary across countries.

Panel A of Table 1 shows the results using all countries in the sample. The growth response variation to temperature is widespread and significant. The homogeneity restrictions are rejected by the data, as the p-values of the test statistics are zero for both temperature measures.

Next, we report that the split between positive and negative betas is not simply a split between rich and poor countries. In panel B, the test is applied only to poor countries–those whose average real GDP per capita over the sample is below the median. Even among poor countries, many have positive growth responses to each of the temperature measures. Of the poor countries, 43 percent of the slope point estimates are positive in regressions with global temperature, and 40 percent with idiosyncratic temperature. The estimated β_p is positive and highly significant. Here as well, the test of the homogeneity restrictions across poor countries is rejected.

The rejections of the homogeneity restrictions shown in Table 1 yields evidence that extensive pooling is not appropriate and the presence of widespread response heterogeneity, even among poor countries.

Table 1: Tests of Extensive Homogeneity Restrictions

			$\beta_p = \beta_n$	
	β_p	β_n	χ^2	p-val
A. All Countries				
Global	2.96	-3.26	80.52	0.00
	(5.64)	(-7.20)		
Idiosyncratic	1.25	-1.64	81.02	0.00
	(5.29)	(-7.54)		
B. Poor Countries				
Global	4.00	-3.41	48.98	0.00
	(5.09)	(-4.80)		
Idiosyncratic	1.72	-2.37	49.84	0.00
	(3.99)	(-6.11)		

Notes: The slope is β_p in the positive beta group and is β_n in the negative beta group. The t-ratio is in parenthesis. A Wald test of the hypothesis $\beta_p = \beta_n$ is χ_1^2 under the null. Global temperature is G_t and idiosyncratic temperature is $I_{j,t}$. Poor countries are those whose average real GDP per capita over the sample is below the median.

4 Impulse Responses by Local Projections

This section first discusses our local projection specification and how estimation with limited pooling of small groups of countries with quantitatively similar responses preserves the individual point estimates while achieving shrinkage in standard errors. Section 4.2 presents our main results.

4.1 Local Projection by Regression and Limited Scale Pseudo Panel Estimation

Our local projections are the sequence of regressions at horizons $h \in \{0, ..., 5\}$ years, estimated separately for each country with at least 30 per capita GDP observations $j \in \{1, ..., 137\}$,

$$100\left(y_{j,t+h} - y_{j,t-1}\right) = \beta_{j,h}^{G} G_t + \beta_{j,h}^{I} I_{j,t} + x_{j,t}^{\prime} \gamma_{j,h} + \epsilon_{j,t+h}, \tag{6}$$

where $y_{j,t}$ is log real GDP per capita of country j at time t, $G_{j,t}$ is global temperature at time t, $I_{j,t}$ is idiosyncratic country j temperature at time t, and $x_{j,t}^{\prime}\gamma_{j,h} = \sum_{k=1}^{K} \delta_{j,h,k} \Delta y_{j,t-k} + \sum_{\ell=1}^{L} \theta_{j,h,\ell} G_{t-\ell} + \sum_{m=1}^{M} \mu_{j,h,m} I_{j,t-m} + c_{j,h}$ are controls consisting of lags of annual real GDP per capita growth, lags of global temperature, lags of idiosyncratic temperature, and the regression constant. Lag lengths K, L, and M are determined by the Akaike's Information Criterion (AIC) for each country j at horizon $h = 0$.[9] As is well-known, AIC tends to lead to overparameterization. For this reason, we use the AIC specifications to guard against omitted variable bias. Here

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[9] The number of lags of global temperature (G), idiosyncratic temperature (I), and real GDP per capita growth (Δy) included in equation (6) for each country according to Akaike's Information Criterion (AIC) are reported in Appendix C.

we again rely on the results of West [1988] and Park and Phillips [1988] to establish our use of including the global temperature, G_t, in levels for our estimations.

The sample length for our countries ranges from 30 to 57 annual observations. As shown by Jordà [2005] and Plagborg-Møller and Wolf [2021], the local projection coefficients are asymptotically equivalent to the impulse response function from a vector autoregression. The local projection coefficients $\beta^G_{j,h}$, give us impulse responses of the percent change in real GDP per capita from time $t-1$ to $t+h$ due to a 1^oC shock in global temperature at time t. $\beta^I_{j,h}$ gives us the impulse responses of the percent change in real GDP per capita from $t-1$ to $t+h$ due to a 1^oC shock in idiosyncratic temperature at time t. Since impulse responses from vector autoregressions are colloquially referred to as responses to 'shocks,' we similarly refer to the local projection estimates as growth responses to temperature 'shocks' even though the regressor is a temperature variable, G_t or $I_{j,t}$ (and not a 'shock' *per se*). To further economize on terminology, we refer to these response coefficients ($\beta^G_{j,h}$ and $\beta^I_{j,h}$) as global/idiosyncratic 'local projection betas.' At horizons $h > 0$, the overlapping dependent variable observations induce serial correlation in the error terms which we address with Newey and West [1987] standard errors.

Small Scale Pseudo-Panel Local Projections. Here, we describe a strategy for shrinking the impulse response standard errors while keeping point estimates close to the single-equation local projection estimates. This is done by constrained estimation of small sets of pseudo-panels for countries with similar sized local projection betas. While extensive pooling was shown to be unjustified, this limited pooling of countries with locally similar sized betas is supported by the data (as we report in the next subsection).

The pseudo-panel estimation proceeds as follows. Begin with country 1 at horizon $h \in \{0, ..., 5\}$. Using the single-equation local projection estimates, compute country 1's SSE (sum of squared errors) relative to the remaining countries, $(\beta^G_{1,h} - \beta^G_{j,h})^2 + (\beta^I_{1,h} - \beta^I_{j,h})^2$, $j \neq 1$ and sort by SSE from lowest to highest. Form country $1's$ pseudo-panel consisting of between two to five countries with the lowest SSEs.[10] Repeat for countries 2 through 137. Index the members of a given pseudo-panel by j and estimate the constrained local projection,

$$100\,(y_{j,t+h} - y_{j,t-1}) = \beta^G_h G_t + \beta^I_h I_{j,t} + x'_{j,t}\gamma_{j,h} + \epsilon_{j,t+h}. \tag{7}$$

Only the global and idiosyncratic local projection betas are constrained to be equal. We refer to these systems as *pseudo-panels* because the group membership can change from one horizon to the next. We estimate the pseudo-panels by generalized method of moments (GMM), where the regressors for each country's equation serve as instruments for that equation. The result is a system of constrained least squares estimation with GMM (system-wide Newey-West) standard errors. As a matter of terminology, we refer to these local projection impulse response coefficients

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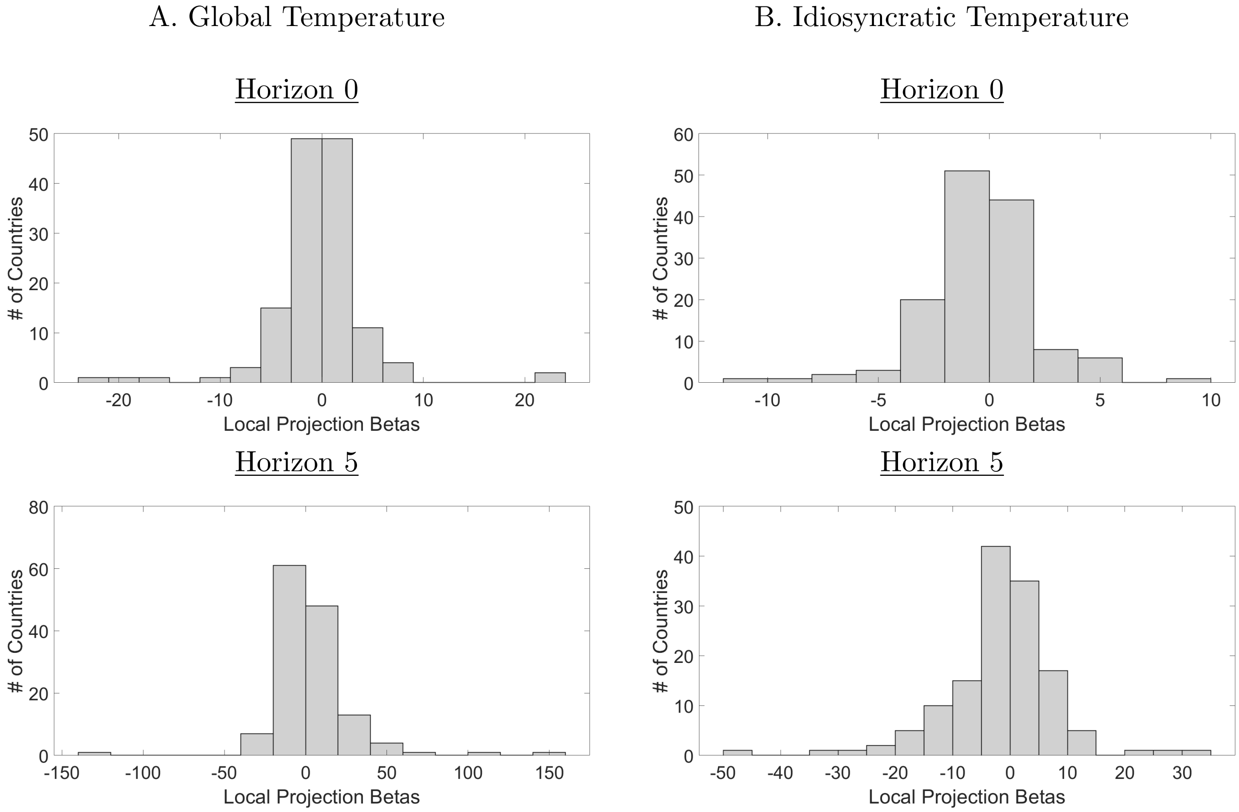
[10] Pseudo-panel sizes are small in cases where there are few similarities.

as global/ idiosyncratic ‘pseudo-panel local projection betas.’

4.2 Local Projections with Global and Idiosyncratic Temperature

This section reports results for the responses of growth to global (G_t) and idiosyncratic ($I_{j,t}$) temperature shocks. We report summaries of the results rather than showing all of the impulse response figures. The full set of impulse responses to global and idiosyncratic temperature shocks are shown in Appendix D.

Figure 3: Global and Idiosyncratic Temperature Local Projection Betas



A. Global Temperature

B. Idiosyncratic Temperature

Horizon 0

Horizon 5

Notes: Distribution of global temperature (G_t) and idiosyncratic temperature ($I_{j,t}$) local projection betas, $\beta^G_{j,h}$ and $\beta^I_{j,h}$, from equation (6) for $j = 1, ..., 137$ and $h = 0$ and 5. Specifications are determined by Akaike's Information Criterion (AIC).

Figure 3 displays the histograms of the global (Panel A) and idiosyncratic (Panel B) temperature local projection betas at horizons 0 and 5. Extensive heterogeneity is observed in the responses. We note that some of the responses are quite large in magnitude because the responses are stated in percent and are for a 1^oC increase in global or idiosyncratic temperature, which is much larger than the normal year-to-year variation in observed temperature. For example, the maximum temperature change in a year for the global component was approximately 0.5^oC in the sample period.

Table 2: Global and Idiosyncratic Temperature Local Projection and Pseudo-Panel Local Projection Summary

A. Global Temperature

	Local Projection Betas						Pseudo-Panel Local Projection Betas					
Horizon	0	1	2	3	4	5	0	1	2	3	4	5
# neg	71	65	67	68	68	69	75	70	69	68	72	71
# pos	66	72	70	69	69	68	62	67	68	69	65	66
# sig neg	15	11	13	16	17	18	47	40	40	40	45	50
# sig pos	7	8	10	11	17	23	33	34	38	44	44	52

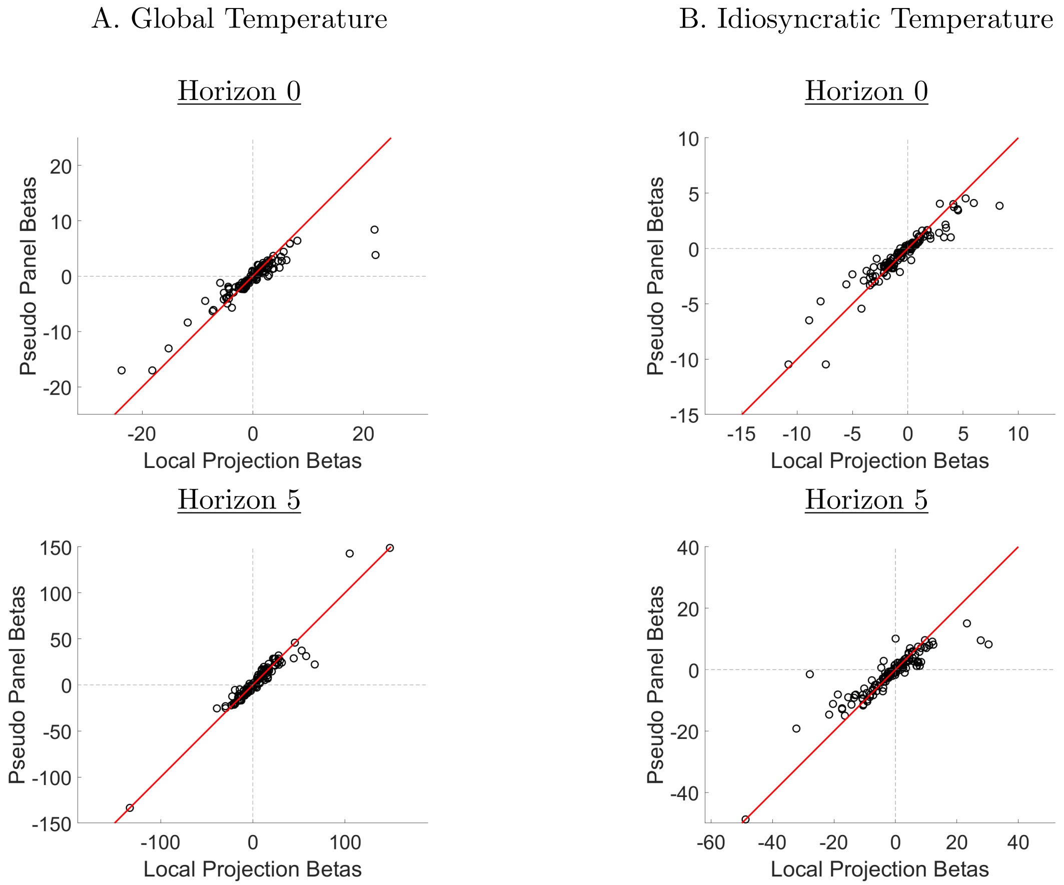
B. Idiosyncratic Temperature

	Local Projection Betas						Pseudo-Panel Local Projection Betas					
Horizon	0	1	2	3	4	5	0	1	2	3	4	5
# neg	78	76	68	78	74	77	77	78	67	75	73	75
# pos	59	61	69	59	63	60	60	59	70	62	64	62
# sig neg	7	6	14	16	14	12	48	51	41	44	49	55
# sig pos	8	8	4	4	4	4	31	41	33	32	34	31

Notes: This table shows the count of global (Panel A) and idiosyncratic (Panel B) temperature local projection (estimates from equation (6)) and pseudo-panel local projection (estimates from equation (7)) betas that are negative (neg), positive (pos), and statistically significant at the 5 percent level (sig neg and sig pos). Specifications are determined by Akaike's Information Criterion (AIC).

Table 2 reports the summary comparison between the local projection and pseudo-panel local projection betas. Panel A shows results for global temperature shocks and Panel B shows results for idiosyncratic shocks. Comparing across estimation methods and horizons reveals similar numbers of positive and negative point estimates but many more statistically significant pseudo-panel estimates. Negative betas often outnumber positive betas for the idiosyncratic temperature shocks (Panel B), but the number of positive and negative betas for the global temperature shock is approximately even (Panel A). The total number of significant negative and significant positive responses to global temperature shocks often dominates those for idiosyncratic temperature shocks.

Figure 4: Scatter Plots of Global and Idiosyncratic Temperature Pseudo-Panel Local Projection Betas and Local Projection Betas


A. Global Temperature

B. Idiosyncratic Temperature

Horizon 0

Horizon 5

Notes: The 45^o line is given in red. Local projection betas are estimates from equation (6) and pseudo panel local projection betas are estimates from equation (7) for $h = 0$ and $h = 5$. Specifications are determined by Akaike's Information Criterion (AIC).

Figure 4 displays scatter plots of the global (Panel A) and idiosyncratic (Panel B) pseudo-panel local projection betas against the local projection betas at horizons 0 and 5. The 45^o line is given in red. This figure provides visual confirmation that the pseudo-panel point estimates lie close to the local projection point estimates in most cases. With very few exceptions the plotted coefficients lie in the 1^{st} and 3^{rd} quadrants, meaning there is agreement on the signs of the coefficients irrespective of the estimation method. Even for the estimates far from the 45^o line, which tend to be closer to the distribution tails, the signs of the coefficients remain in agreement.

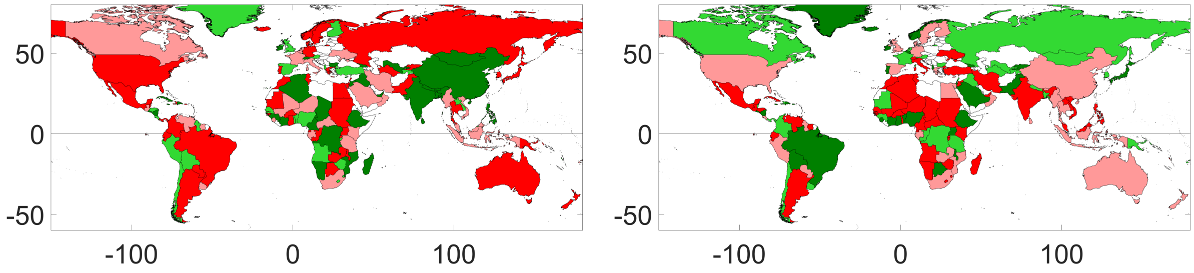
Figure 5: Global and Idiosyncratic Temperature Pseudo-Panel Local Projection Betas

A. Global Temperature

B. Idiosyncratic Temperature

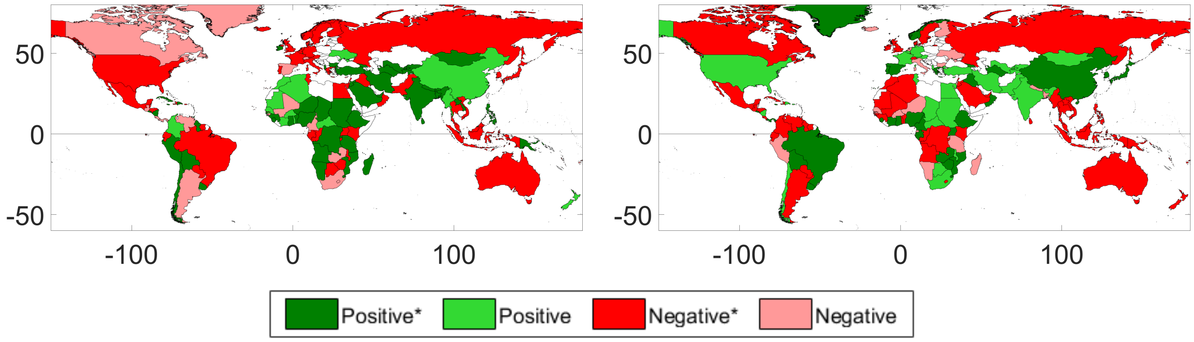
Horizon 0

Horizon 0



Horizon 5

Horizon 5



Notes: Global (Panel A) and idiosyncratic (Panel B) temperature pseudo-panel local projection betas, $\beta_{j,h}$, are from equation (7) for $h = 0$ and $h = 5$. Specifications are determined by Akaike's Information Criterion (AIC). * indicates significance at the 5 percent level.

Figure 5 plots the pseudo-panel local projection betas at horizons 0 and 5 onto a world map. Results for global temperature shocks are in Panel A and idiosyncratic temperature shocks in Panel B. Negative responses are shown in red and positive responses in green. Darker shades indicate statistical significance at the 5 percent level.

Let us look at the response to global temperature shocks. At horizon 0, negative responses are found for both high (e.g., Denmark, South Korea, and Norway) and low (e.g., Zambia, Uganda, and Ghana) income countries. At horizon 5, negative responses are found primarily for rich countries. All of the Group of 7 (G-7) country responses are negative and of these all but Canada's are significantly so. Surprisingly, some of the poorest countries experience significantly positive growth responses to positive global temperature shocks. This include large swaths in Sub-Saharan Africa and South Asia. Some of the larger oil producing countries in OPEC have significantly positive responses by horizon 5 such as Angola, Iran, Nigeria, Saudi Arabia, and UAE. However, Iraq's is significantly negative while Venezuela's (-) and Algeria's (+) are both insignificant.

Next, we look at the response to idiosyncratic temperature shocks. Here, at horizons 0 and 5, negative responses outnumber positive ones and there is less of a pattern amongst rich countries. At horizon 5, the response of the UK and Canada are significantly negative but is significantly positive for Japan. At longer horizons, the coefficient signs are negative for many countries in Southeast Asia and Oceana, Nigeria, Mexico, and Russia.

Interestingly, a visual comparison across shocks within each horizon shows the direction of a country's response are sometimes at odds with each other. Prominent examples include Brazil and India at horizon 0, and large oil states such as Angola, Saudi Arabia, and UAE at horizon 5. The same sized coefficients on global and idiosyncratic temperature should not be interpreted to mean the two temperature components are equally important. Global temperature is trending up while idiosyncratic temperature is, by construction, stationary around zero. This makes the global temperature shocks quantitatively more important.

Figure 6 displays the pseudo-panel impulse responses to global and idiosyncratic temperature shocks for a set of rich (Panel A) and poor (Panel B) countries. The rich are represented by the G-7 countries plus Australia and China and the poor are the nine poorest countries in our sample, based on average real GDP per capita over the sample.[11] Amongst the rich, except for China and the UK, real GDP per capita initially declines following an increase in global temperature. The responses are more mixed following an increase in idiosyncratic temperature. Amongst the poorest countries, real GDP per capita increases on impact from a positive global country temperature shock and a positive idiosyncratic temperature shock in Ethiopia and Nepal.

To summarize this section, the local projection and pseudo-panel local projection results establish three main findings. First, there is substantial heterogeneity in the responses across countries, irrespective of the source of temperature fluctuations. Second, the variation in growth responses from the two sources of temperature fluctuations highlights the importance of separately considering idiosyncratic, country-specific from global temperature change. While the signs of the growth responses from global and idiosyncratic temperatures often coincide, there are many instances where they go in opposite directions. Finally, we show the most developed countries evidently face substantial economic damages from global temperature change.

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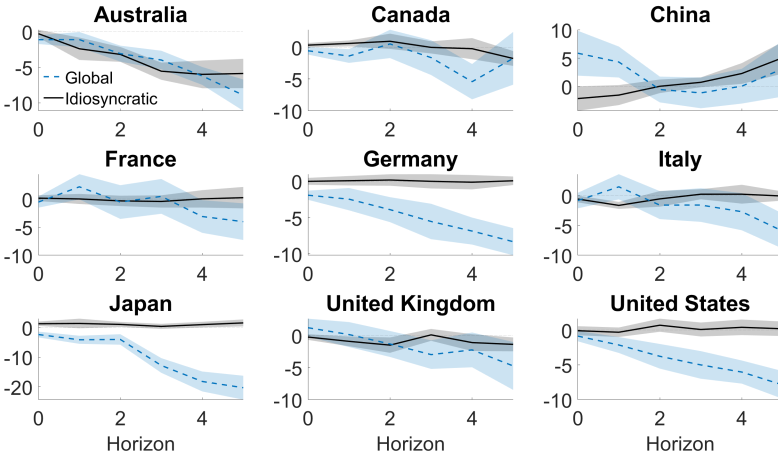
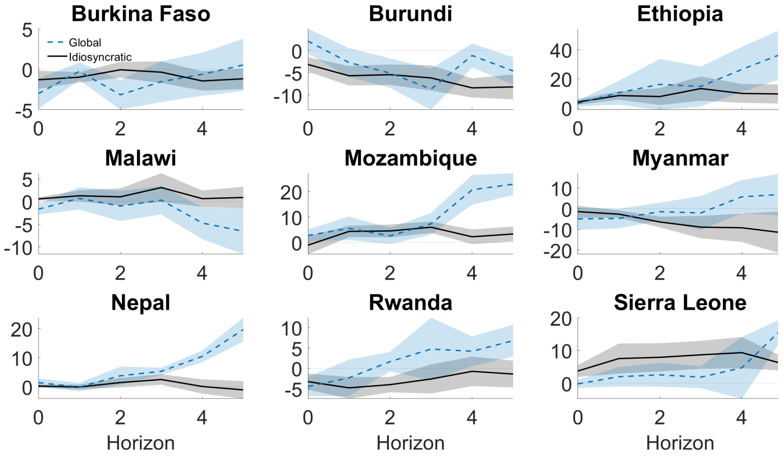
[11] China is grouped with the rich countries, not on the basis of per capita GDP but because it is the world's second largest economy.

Figure 6: Pseudo-Panel Impulse Responses of Growth to Global (Dashed) and Idiosyncratic (Solid) Temperature Shocks–Selected Rich and Poor Countries

A. G-7 Plus Australia and China



B. Nine Poorest Countries



Notes: Shaded areas are plus and minus 1.96 standard error bands.

5 Cross-Sectional Response Heterogeneity and Country Characteristics

What explains the response heterogeneity across countries? This section investigates how country characteristics, including geographic, economic, demographic, and political factors can explain the variation in responses. The analysis is based on a cross-sectional regression of the global/idiosyncratic local projection betas on these country characteristics.[12] Although the betas are estimated, there is no 'second stage' or generated regressors problem because the estimated response coefficients are the dependent variable in the regressions. If X_j is the vector of country $j's$ characteristics and the constant, we run the cross-sectional regression

$$\hat{\beta}^{\tau}_{j,h} = X'_j \gamma_{\tau,h} + u_{\tau,h}, \tag{8}$$

of the idiosyncratic and global impulse response estimates $\tau = I, G$ at horizons $h = 0, \ldots, 5$.

The variables we use are based on the following considerations. We are primarily interested in the explanatory power of various economic characteristics after controlling for geographic variables. In light of panel studies finding response differences between rich and poor countries, we include average real GDP per capita in logarithmic form. Extant research would lead one to expect log income to enter with a positive coefficient. We also consider a country's long-horizon growth rate, which is the growth rate of real GDP per capita (Growth) from beginning to the end of the sample. The country's average openness (Openness), which are exports plus imports as a share of GDP, captures the degree of economic connectedness to the rest of the world. We also include the average GDP share of agriculture since agriculture has long been seen as a very direct channel through which temperature affects the economy. Agricultural workers, especially in poorer countries, are directly exposed to temperature as are the crops themselves, and Deryugina and Hsiang [2014], Deschênes and Greenstone [2007], Nelson et al. [2014], and Dietz and Lanz [2019] report empirical damage estimates to agriculture from high temperatures. Average high-school attainment gives a coarse measure of human capital accumulated and democracy examines the potential role of political responses to temperature.

Except for latitude and temperature, the data are from the World Bank's, *World Development Indicators* and are the country's time series average over the available sample span. Democracy is the World Bank's Index of Democratization. Absolute latitude and temperature are included primarily as control variables.

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[12] Recently, Lustig and Richmond [2020] employed the same methodology to regress exchange rate betas on gravity variables.

Table 3: Correlation Matrix of Explanatory Variables

	L.T. Growth	Openness	High School	Democracy	Agricultural Share	Latitude	Temperature
log(GDP Per Capita)	0.144	0.256	0.705	0.738	-0.885	0.032	-0.529
L.T. Growth		-0.028	0.089	0.147	-0.126	-0.028	-0.161
Openness			0.185	0.117	-0.297	-0.140	-0.097
High School				0.617	-0.618	0.017	-0.688
Democracy					-0.603	0.077	-0.615
Agricultural Share						0.007	0.453
Latitude							-0.065

Table 3 shows the correlations amongst these variables. Country latitude is only slightly negatively correlated with high-school attainment but is roughly uncorrelated with all other variables. The inverse relationship between temperature and growth in the cross-section (correlation -0.529) has been well studied [Dell et al., 2009]. In what follows, we present specifications with the entire list of variables together as regressors to mitigate potential omitted variables bias.

Table 4: Cross-Sectional Regression with Idiosyncratic Temperature Local Projection Betas

	Horizon					
	0	1	2	3	4	5
log(GDP Per Capita)	-0.197	-0.562	-0.725	-0.975	-0.915	-1.132
	(-0.685)	(-1.219)	(-1.113)	(-1.313)	(-1.158)	(-1.274)
L.T. Growth	0.051	0.188	0.144	0.552	0.494	0.899
	(0.240)	(0.550)	(0.299)	(1.005)	(0.843)	(1.367)
Openness	0.001	0.003	-0.005	-0.009	-0.011	-0.005
	(0.204)	(0.428)	(-0.419)	(-0.692)	(-0.771)	(-0.307)
High School	0.011	0.024	0.030	0.046*	**0.066**	0.038
	(1.185)	(1.603)	(1.450)	(1.930)	(2.602)	(1.356)
Democracy	0.023	0.043	-0.009	-0.014	-0.064	-0.013
	(1.020)	(1.192)	(-0.169)	(-0.241)	(-1.032)	(-0.184)
Agricultural Share	-0.003	0.022	-0.014	-0.028	-0.020	-0.025
	(-0.115)	(0.489)	(-0.219)	(-0.388)	(-0.263)	(-0.290)
Latitude	-0.006	0.003	0.006	0.008	0.007	0.047
	(-0.683)	(0.214)	(0.306)	(0.353)	(0.298)	(1.662)
Temperature	-0.016	0.022	-0.031	-0.034	-0.044	-0.111
	(-0.492)	(0.420)	(-0.417)	(-0.407)	(-0.499)	(-1.113)
R-Square	0.068	0.058	0.043	0.070	0.101	0.097
Observations	122	122	122	122	122	122

Notes: T-ratios in parentheses. Except for latitude and temperature, variables are from the *World Development Indicators*. Significance at the 5% level indicated by bold face and at the 10% level by '*'.

We begin with the idiosyncratic temperature betas. Table 4 shows results. Almost none of the estimates are significant. The only exceptions are average high-school attainment at horizons 3 and 4. GDP response to idiosyncratic temperature shocks are unsystematic in the sense that their variation is largely unexplained by country characteristics.

Table 5: Cross-Sectional Regression with Global Temperature Local Projection Betas

	Horizon					
	0	1	2	3	4	5
log(GDP Per Capita)	0.133	-1.306	-1.411	**-3.029**	-4.177*	-4.450
	(0.288)	(-1.644)	(-1.308)	(-2.070)	(-1.935)	(-1.452)
L.T. Growth	0.261	**-1.511**	**-2.548**	**-4.258**	**-6.138**	**-7.122**
	(0.768)	(-2.569)	(-3.193)	(-3.931)	(-3.841)	(-3.138)
Openness	0.011	**0.037**	**0.052**	**0.070**	**0.103**	**0.132**
	(1.304)	(2.619)	(2.720)	(2.731)	(2.694)	(2.435)
High School	0.013	**0.075**	**0.131**	**0.236**	**0.382**	**0.483**
	(0.903)	(2.953)	(3.824)	(5.049)	(5.555)	(4.945)
Democracy	-0.029	-0.030	-0.141*	**-0.225**	**-0.458**	**-0.720**
	(-0.823)	(-0.483)	(-1.685)	(-1.972)	(-2.725)	(-3.019)
Agricultural Share	0.028	0.034	0.094	0.065	0.157	0.378
	(0.628)	(0.441)	(0.892)	(0.458)	(0.746)	(1.268)
Latitude	**-0.029**	-0.043*	-0.047	-0.048	-0.055	-0.033
	(-2.026)	(-1.728)	(-1.375)	(-1.036)	(-0.813)	(-0.338)
Temperature	0.029	-0.031	-0.048	0.009	-0.135	-0.422
	(0.553)	(-0.352)	(-0.397)	(0.057)	(-0.556)	(-1.223)
R-Square	0.080	0.244	0.315	0.394	0.429	0.398
Observations	122	122	122	122	122	122

See notes to Table 4.

Next, we turn to the global temperature betas. To suggest a mechanism for global temperature, let us think of each country as a small-open economy. Then the effect of temperature on GDP need not be restricted to temperature within its borders. While some part of a global temperature shock may represent the direct effect of country temperature on GDP, a good portion may also be the effect on the rest-of-world (ROW) economy and subsequent indirect effects on individual countries through trade and finance linkages. Countries vary in their exposure to changes in global economic conditions induced by temperature shocks.

Table 5 shows regression results for the global temperature betas and tells quite a different story. At horizons 3-5, GDP, growth, openness, high-school and democracy are generally significant. A country is more likely to have a *positive* GDP response to increased global temperature if it is poorer, has grown less rapidly, is more open to trade, more educated, and more authoritarian. Average temperature is never significant, and latitude only at horizons 0 and 1. Interestingly, the GDP share of agriculture is never significant.

The negative point estimates on log GDP and growth largely confirm impressions from viewing the maps in Figure 4. The positive coefficient on openness is consistent with the following: suppose the global temperature shock has the effect of an uncertainty shock and has a larger effect on colder and richer countries. This affects these countries like a negative aggregate demand shock which improves the terms of trade for poorer and hotter countries. Countries that are more open to trade are able to benefit from this.[13] Indeed, Lee et al. [2022] find, at the four year horizon, exchange rates tend to appreciate for hotter, open countries from temperature shocks.[14]

The positive coefficient on high-school suggests that a more educated country is better equipped to deal with higher temperature through innovation and adaptation.

The negative coefficient on democracy may indicate lower bargaining power of labor in authoritarian regimes where resources are concentrated and under control of a small number of elites. We emphasize that our results are about the potential role of democracy on how a country responds to temperature shocks and not on the relationship between democracy and growth *per se*.[15] Another potential explanation relates to Tavares and Wacziarg [2001] who find democracy hinders growth because more democratic countries channel more resources to the poor which comes at the expense of capital accumulation. Hence, if temperature change and warming disproportionately afflicts the poor, it may be that more democratic countries respond to temperature change by redirecting resources to those most afflicted instead of towards avenues that promote growth. In contrast, less democratic countries may opt to neglect resource redistribution to those most vulnerable to warming.

6 Conclusion

This paper reexamines the relationship between rising temperature and real GDP per capita growth, but from a country-specific time series perspective using local projections [Jordà, 2005]. We examine the growth responses from both country-specific (idiosyncratic) and common, global temperature variation. We find substantial heterogeneity across countries in the impulse responses of real GDP per capita growth to shocks to our temperature components–more than was previously reported in the literature. Qualitatively consistent with the previous literature though, there are more negative than positive impulse responses of real GDP per capita growth to increases in idiosyncratic temperature. On the other hand, approximately half of the countries across all horizons have positive responses to global temperature change. Richer countries, in particular,

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[13] Berg and Mark [2022] show how an uncertainty shock causes terms-of trade deterioration in the country experiencing the shock.

[14] This is not the same for climate disasters. Hale [2022] shows safe country currencies appreciate relative to risky country currencies following a climate disaster shock.

[15] There is a vast literature on the role of democracy on growth, but the relationship is still debated. Studies finding positive effects include Acemoglu et al. 2019, Colagrossi et al. 2020 and references therein. Studies finding negative or nil effects include Gerring et al. 2005 and references therein and among others.

such as the United States, tend to experience negative impulse responses of real GDP per capita growth to increases in global temperature.

We find growth responses are statistically significantly positive for many countries, including some of the poorest ones, from global temperature variation. We believe these results are robust to observed historical GDP and temperature variation. However, we are less certain of the stability of these relationships when projecting forward. It would be highly speculative to think that the historical relationship between temperature and growth will continue in the future if global temperature rises 2^o-4^o Celsius. For this reason, we did not use our results to assess future damage.

Our analysis also investigates the country-level characteristics that might explain variation in the estimated growth responses to temperature change. These country characteristics did not explain growth responses to idiosyncratic temperature change. Responses to idiosyncratic temperature shocks are largely unsystematic. Variation in response to global temperature shocks are systematically related to several country-level characteristics. A country's GDP is more likely to respond positively to a global temperature shock if it is poorer, has grown less rapidly, is more open to trade, more educated, and more authoritarian.

Our results may be helpful in framing climate change policy. As an ethical matter, Stern [2008] argues that rich countries should pay more for greenhouse gas abatement than developing countries, since the industrialized world has been responsible for emitting most of the current stock of greenhouse gasses. Beyond these ethical considerations, our findings that global temperature increases have resulted in significant economic damages to rich countries suggests that they have a self-interest in investing in abatement policies. If environmental policy is informed by historical relationships – and we show that direction of the growth responses are not uniform across countries – our results also suggest another challenge in forming a global consensus on future abatement strategies.

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Appendix (Not Intended for Publication)

A Country Code, Country Name, and Sample Time Period

Table A1: Country Code, Country Name, and Sample Time Period

Code	Country Name	Sample	Code	Country Name	Sample
AGO	Angola	1980 – 2017	ESP	Spain	1960 – 2017
ALB	Albania	1980 – 2017	ETH	Ethiopia	1981 – 2017
ARE	United Arab Emirates	1975 – 2017	FIN	Finland	1960 – 2017
ARG	Argentina	1960 – 2017	FJI	Fiji	1960 – 2017
AUS	Australia	1960 – 2017	FRA	France	1960 – 2017
AUT	Austria	1960 – 2017	GAB	Gabon	1960 – 2017
BDI	Burundi	1960 – 2017	GBR	United Kingdom	1960 – 2017
BEL	Belgium	1960 – 2017	GEO	Georgia	1965 – 2017
BEN	Benin	1960 – 2017	GHA	Ghana	1960 – 2017
BFA	Burkina Faso	1960 – 2017	GIN	Guinea	1986 – 2017
BGD	Bangladesh	1960 – 2017	GMB	Gambia, The	1966 – 2017
BGR	Bulgaria	1980 – 2017	GNB	Guinea-Bissau	1970 – 2017
BHS	Bahamas, The	1960 – 2017	GNQ	Equatorial Guinea	1980 – 2017
BLZ	Belize	1960 – 2017	GRC	Greece	1960 – 2017
BOL	Bolivia	1960 – 2017	GRL	Greenland	1970 – 2017
BRA	Brazil	1960 – 2017	GTM	Guatemala	1960 – 2017
BRN	Brunei Darussalam	1974 – 2017	GUY	Guyana	1960 – 2017
BTN	Bhutan	1980 – 2017	HND	Honduras	1960 – 2017
BWA	Botswana	1960 – 2017	HTI	Haiti	1960 – 2017
CAF	Central African Republic	1960 – 2017	IDN	Indonesia	1960 – 2017
CAN	Canada	1970 – 2017	IND	India	1960 – 2017
CHE	Switzerland	1970 – 2017	IRL	Ireland	1970 – 2017
CHL	Chile	1960 – 2017	IRN	Iran, Islamic Rep.	1960 – 2017
CHN	China	1960 – 2017	IRQ	Iraq	1968 – 2017
CIV	Cote d'Ivoire	1960 – 2017	ISL	Iceland	1970 – 2017
CMR	Cameroon	1960 – 2017	ISR	Israel	1960 – 2017
COD	Congo, Dem. Rep.	1960 – 2017	ITA	Italy	1960 – 2017
COG	Congo, Rep.	1960 – 2017	JAM	Jamaica	1966 – 2017
COL	Colombia	1960 – 2017	JOR	Jordan	1975 – 2017
COM	Comoros	1980 – 2017	JPN	Japan	1960 – 2017
CPV	Cabo Verde	1980 – 2017	KEN	Kenya	1960 – 2017
CRI	Costa Rica	1960 – 2017	KGZ	Kyrgyz Republic	1986 – 2017
CUB	Cuba	1970 – 2017	KOR	Korea, Rep.	1960 – 2017
CYP	Cyprus	1975 – 2017	LAO	Lao PDR	1984 – 2017
DEU	Germany	1970 – 2017	LBN	Lebanon	1988 – 2017
DNK	Denmark	1960 – 2017	LKA	Sri Lanka	1961 – 2017
DOM	Dominican Republic	1960 – 2017	LSO	Lesotho	1960 – 2017
DZA	Algeria	1960 – 2017	LUX	Luxembourg	1960 – 2017
ECU	Ecuador	1960 – 2017	MAR	Morocco	1966 – 2017
EGY	Egypt, Arab Rep.	1960 – 2017	MDG	Madagascar	1960 – 2017

Table A2: Country Code, Country Name, and Sample Time Period (Continued)

Code	Country Name	Sample
MEX	Mexico	1960 – 2017
MLI	Mali	1967 – 2017
MMR	Myanmar	1960 – 2017
MNG	Mongolia	1981 – 2017
MOZ	Mozambique	1980 – 2017
MRT	Mauritania	1961 – 2017
MWI	Malawi	1960 – 2017
MYS	Malaysia	1960 – 2017
NAM	Namibia	1980 – 2017
NER	Niger	1960 – 2017
NGA	Nigeria	1960 – 2017
NIC	Nicaragua	1960 – 2017
NLD	Netherlands	1960 – 2017
NOR	Norway	1960 – 2017
NPL	Nepal	1960 – 2017
NZL	New Zealand	1970 – 2017
OMN	Oman	1965 – 2017
PAK	Pakistan	1960 – 2017
PAN	Panama	1960 – 2017
PER	Peru	1960 – 2017
PHL	Philippines	1960 – 2017
PNG	Papua New Guinea	1960 – 2017
PRI	Puerto Rico	1960 – 2017
PRT	Portugal	1960 – 2017
PRY	Paraguay	1960 – 2017
RUS	Russian Federation	1989 – 2017
RWA	Rwanda	1960 – 2017
SAU	Saudi Arabia	1968 – 2017
SDN	Sudan	1960 – 2017
SEN	Senegal	1960 – 2017
SLE	Sierra Leone	1960 – 2017
SLV	El Salvador	1965 – 2017
SUR	Suriname	1960 – 2017
SWE	Sweden	1960 – 2017
SWZ	Eswatini	1970 – 2017
TCD	Chad	1960 – 2017
TGO	Togo	1960 – 2017
THA	Thailand	1960 – 2017
TJK	Tajikistan	1985 – 2017
TKM	Turkmenistan	1987 – 2017
TTO	Trinidad and Tobago	1960 – 2017
TUN	Tunisia	1965 – 2017
TUR	Turkey	1960 – 2017
TZA	Tanzania	1988 – 2017
UGA	Uganda	1982 – 2017
UKR	Ukraine	1987 – 2017
URY	Uruguay	1960 – 2017
USA	United States	1960 – 2017
UZB	Uzbekistan	1987 – 2017
VCT	St. Vincent and the Grenadines	1960 – 2017
VEN	Venezuela, RB	1960 – 2017
VNM	Vietnam	1984 – 2017
VUT	Vanuatu	1979 – 2017
WSM	Samoa	1982 – 2017
ZAF	South Africa	1960 – 2017
ZMB	Zambia	1960 – 2017
ZWE	Zimbabwe	1960 – 2017

B Temperature Endogeneity with Changes in GDP Per Capita

Our temperature data relies on gridded temperature data which interpolates temperature among the ground station weather readings. This data thus adjusts for missing data from ground stations. One concern is that the underlying ground station weather availability used for interpolation may vary by location, potentially producing inaccurate temperature readings in interpolation that is correlated with economic outcomes – our variable of interest (for example, see Schultz and Mankin [2019] who discuss weather station (dis)continuity during civil conflict risk). Here, we test whether missing temperature observations at ground stations is correlated with our variable of interest, GDP per capita growth. We use ground station temperature reading availability from the Global Historical Climatology Network (GHCN) dataset. This is the data source our gridded temperature data uses.

To measure temperature station availability, for each country we identify the total number of weather stations in our sample period. For each year, we then find the number of stations with complete temperature availability as a share of the total number of stations, *share coverage*. Table B1 reports regression results of share coverage on GDP per capita growth and controls. Columns (1) is a simple regression of *share coverage* on GDP per capita growth and columns (2) and (3) add controls for country and time fixed effects. Column (4) includes a poor dummy (GDP per capita below median for that year) and interaction of poor dummy with GDP per capita growth to investigate whether station availability is driven by relatively poorer countries. Across all specifications, the coefficients on GDP growth and the interaction term are not significant. We conclude that there is not evidence that temperature availability – and thus measurement error – is correlated with GDP per capita growth.

Table B1: Share of Stations with Temperature Coverage

	(1)	(2)	(3)	(4)
$\Delta y_{j,t}$	0.787	0.139	0.162	-0.867
	(1.28)	(0.26)	(0.34)	(-0.91)
$\Delta y_{j,t} \times poor$				1.387
				(1.28)
Country FE	No	Yes	Yes	Yes
Time FE	No	No	Yes	Yes
Poor Dummy	No	No	No	Yes
R^2	0.000	0.300	0.493	0.493
Observations	6135	6135	6135	6135

Note: T-ratios in parentheses

C Local Projections Specifications - Akaike's Information Criterion (AIC)

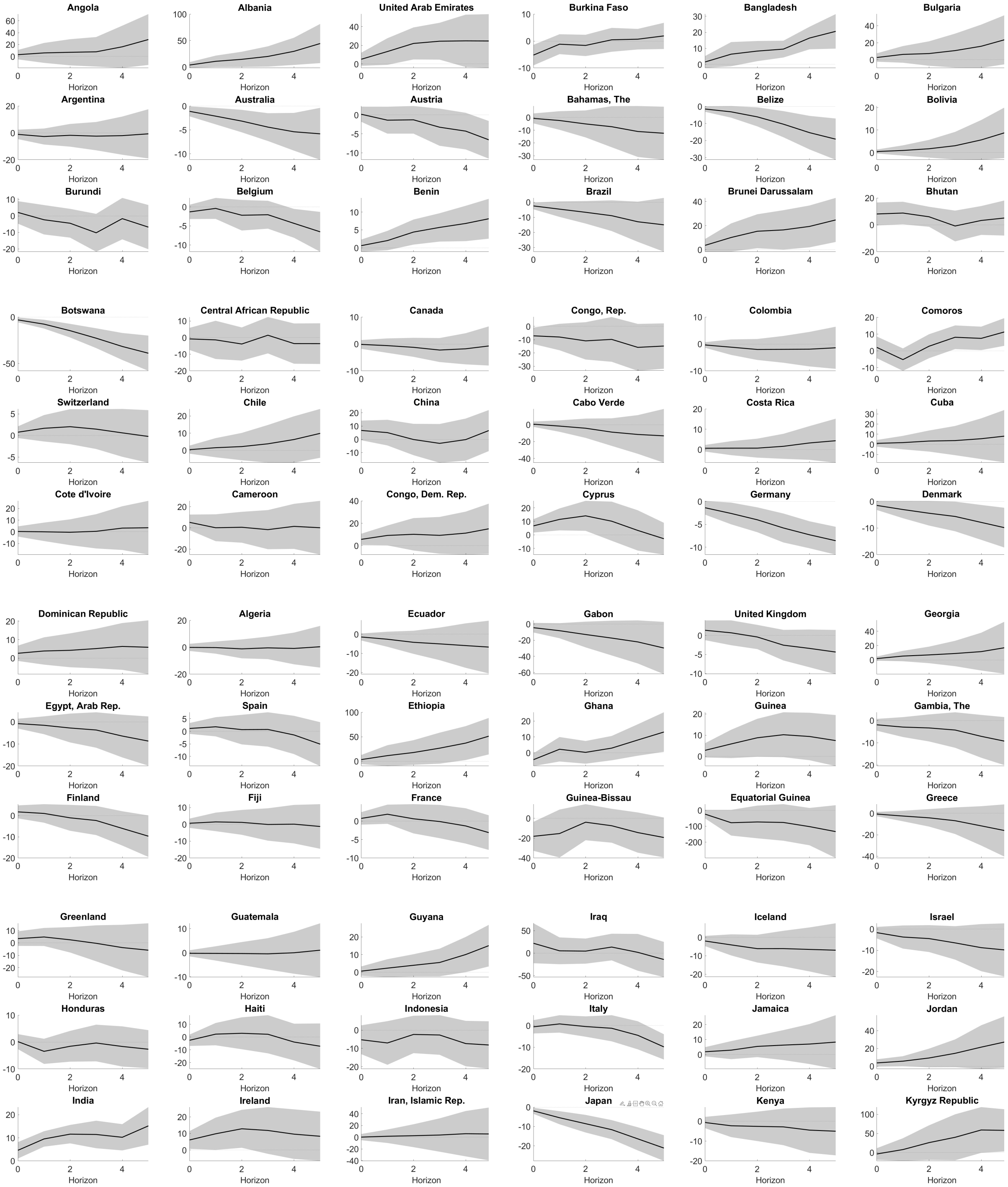
Table C1: Local Projections Specifications - Akaike's Information Criterion (AIC)

Country	Lags of			Country	Lags of			Country	Lags of			Country	Lags of		
Code	G	I	Δy	Code	G	I	Δy	Code	G	I	Δy	Code	G	I	Δy
AGO	0	0	1	ESP	1	0	1	MEX	0	0	0	TTO	0	0	2
ALB	0	0	1	ETH	0	0	4	MLI	0	0	0	TUN	2	0	0
ARE	0	0	4	FIN	1	1	1	MMR	2	0	4	TUR	0	0	0
ARG	0	0	0	FJI	0	0	0	MNG	0	1	2	TZA	1	0	4
AUS	0	1	2	FRA	2	1	2	MOZ	0	1	4	UGA	2	1	4
AUT	1	1	1	GAB	0	0	1	MRT	1	0	4	UKR	1	0	1
BDI	1	0	4	GBR	1	0	2	MWI	2	0	0	URY	0	0	2
BEL	2	0	0	GEO	0	0	2	MYS	0	0	0	USA	0	0	2
BEN	0	0	3	GHA	2	0	2	NAM	0	0	1	UZB	0	0	4
BFA	1	1	0	GIN	0	0	0	NER	0	0	0	VCT	0	0	3
BGD	1	0	0	GMB	0	1	1	NGA	0	0	1	VEN	0	0	0
BGR	0	0	0	GNB	2	0	1	NIC	0	1	3	VNM	0	0	2
BHS	0	0	1	GNQ	2	0	1	NLD	2	0	4	VUT	0	0	4
BLZ	0	0	1	GRC	0	0	3	NOR	0	0	1	WSM	1	0	0
BOL	0	0	2	GRL	2	1	1	NPL	0	0	4	ZAF	2	1	1
BRA	0	0	1	GTM	0	1	3	NZL	1	1	4	ZMB	2	0	4
BRN	0	1	4	GUY	0	0	4	OMN	0	0	3	ZWE	0	1	1
BTN	1	0	0	HND	2	0	4	PAK	0	0	0				
BWA	0	0	1	HTI	2	0	2	PAN	1	0	1				
CAF	1	1	0	IDN	2	0	3	PER	0	0	1				
CAN	0	0	2	IND	1	1	4	PHL	0	0	1				
CHE	0	1	2	IRL	1	0	1	PNG	0	1	1				
CHL	0	0	1	IRN	0	0	1	PRI	0	0	1				
CHN	2	0	3	IRQ	1	0	1	PRT	0	0	4				
CIV	0	0	4	ISL	0	0	4	PRY	0	0	1				
CMR	2	1	3	ISR	0	0	3	RUS	1	1	3				
COD	1	0	3	ITA	2	0	1	RWA	1	0	1				
COG	1	0	3	JAM	0	0	4	SAU	0	0	2				
COL	0	0	1	JOR	0	0	4	SDN	1	1	3				
COM	2	0	4	JPN	0	0	1	SEN	2	0	1				
CPV	0	0	1	KEN	0	1	1	SLE	0	0	0				
CRI	0	0	1	KGZ	1	0	4	SLV	0	0	2				
CUB	0	0	1	KOR	1	0	0	SUR	0	0	1				
CYP	2	0	1	LAO	0	0	4	SWE	0	1	1				
DEU	0	0	2	LBN	0	1	4	SWZ	1	1	1				
DNK	0	0	4	LKA	0	0	1	TCD	0	0	0				
DOM	0	0	2	LSO	2	0	2	TGO	0	0	0				
DZA	0	0	4	LUX	2	1	0	THA	0	0	1				
ECU	0	0	1	MAR	0	1	3	TJK	0	1	4				
EGY	0	0	3	MDG	0	0	0	TKM	2	0	4				

Notes: This table reports the number of lags of global temperature (G), idiosyncratic temperature (I), and real GDP per capita growth (Δy) included in equation (6) for each country according to Akaike's Information Criterion (AIC).

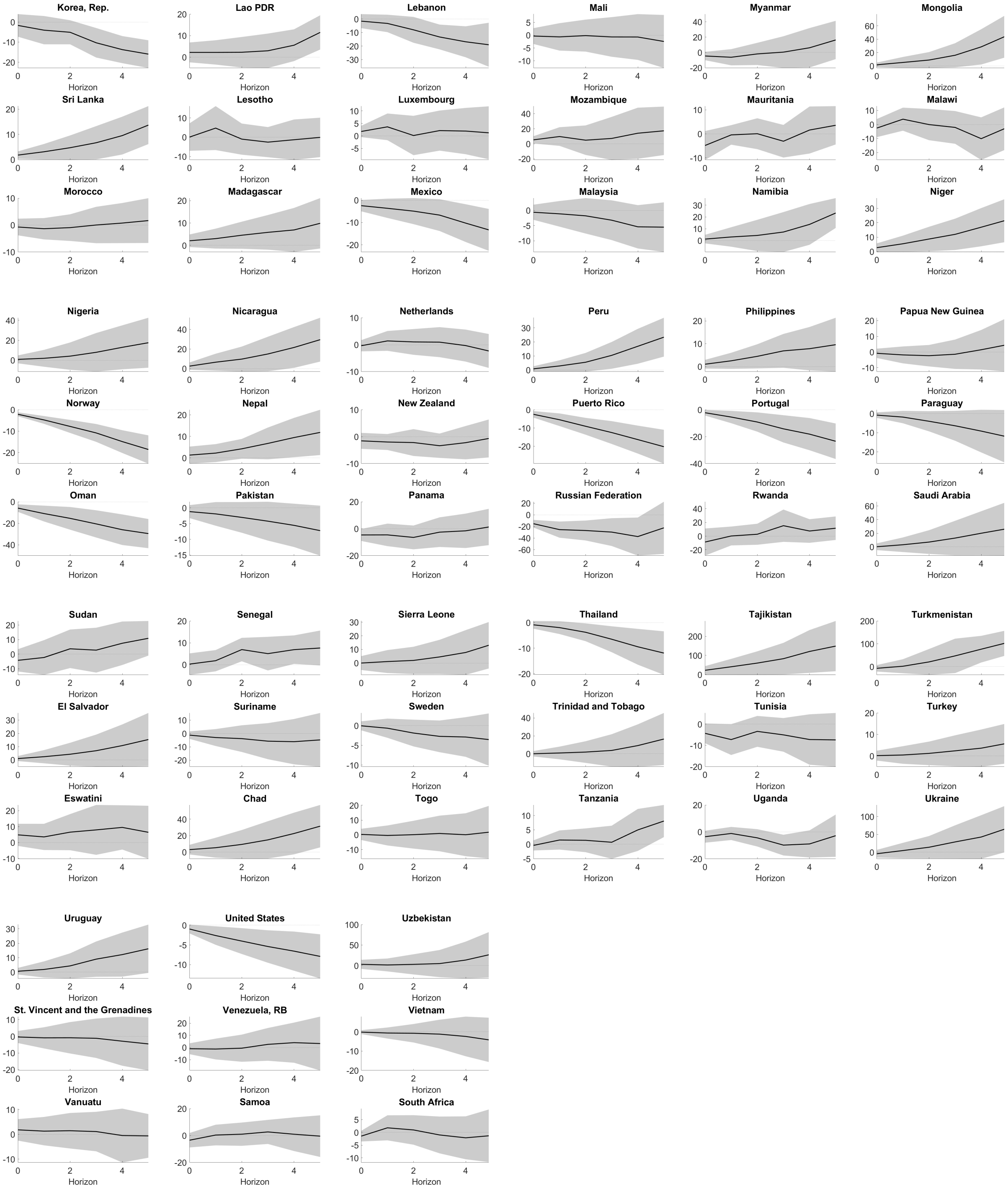
D Global and Idiosyncratic Temperature Local Projection and Pseudo-Panel Local Projection Results

Figure D1: Global Temperature Local Projection Impulse Responses



Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

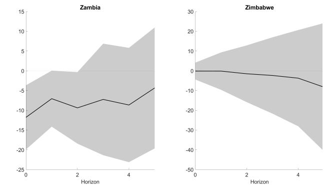
Figure D2: Global Temperature Local Projection Impulse Responses (Continued)



Korea, Rep. · Lao PDR · Lebanon · Mali · Myanmar · Mongolia · Sri Lanka · Lesotho · Luxembourg · Mozambique · Mauritania · Malawi · Morocco · Madagascar · Mexico · Malaysia · Namibia · Niger · Nigeria · Nicaragua · Netherlands · Peru · Philippines · Papua New Guinea · Norway · Nepal · New Zealand · Puerto Rico · Portugal · Paraguay · Oman · Pakistan · Panama · Russian Federation · Rwanda · Saudi Arabia · Sudan · Senegal · Sierra Leone · Thailand · Tajikistan · Turkmenistan · El Salvador · Suriname · Sweden · Trinidad and Tobago · Tunisia · Turkey · Eswatini · Chad · Togo · Tanzania · Uganda · Ukraine · Uruguay · United States · Uzbekistan · St. Vincent and the Grenadines · Venezuela, RB · Vietnam · Vanuatu · Samoa · South Africa

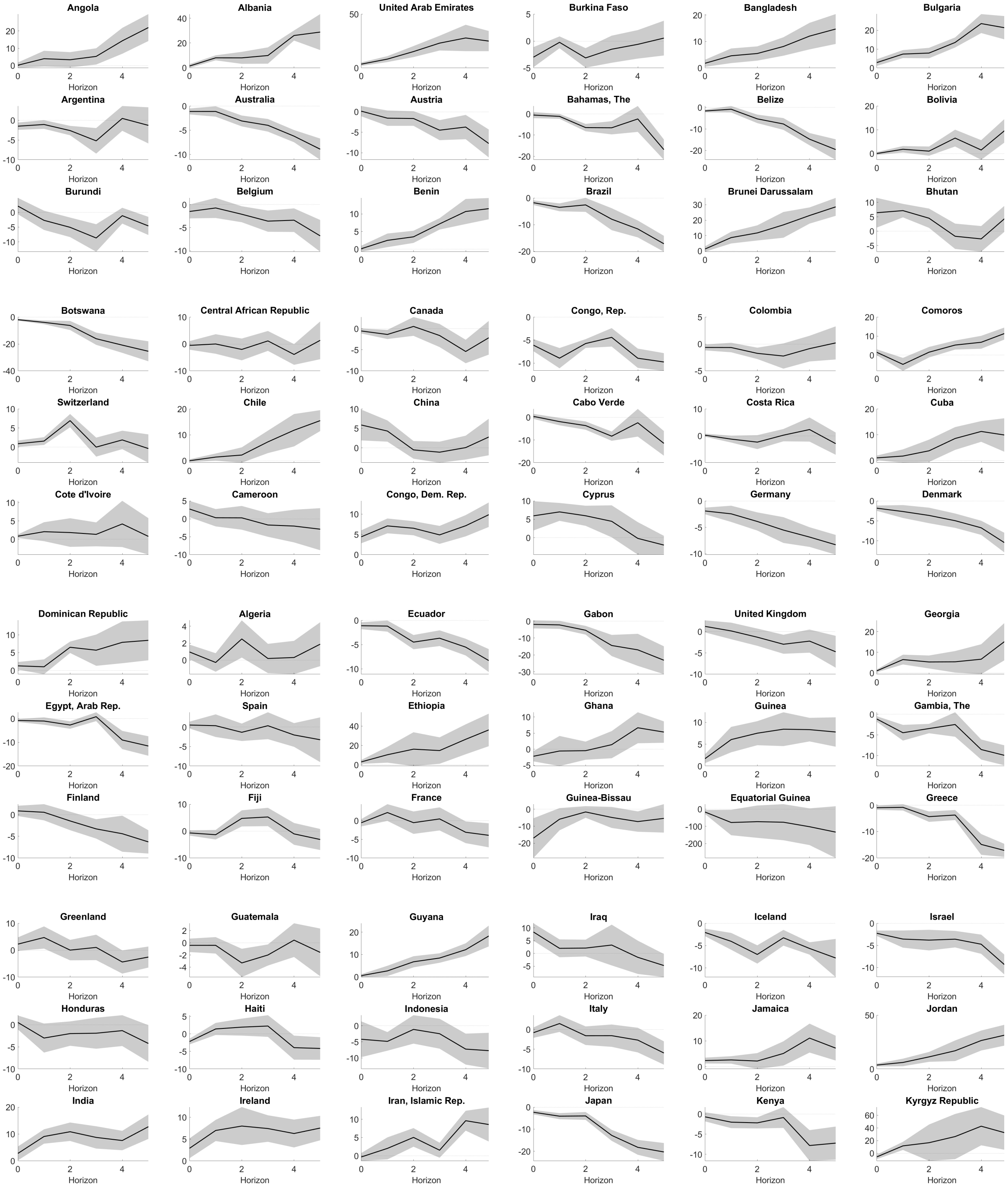
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D3: Global Temperature Local Projection Impulse Responses (Continued)



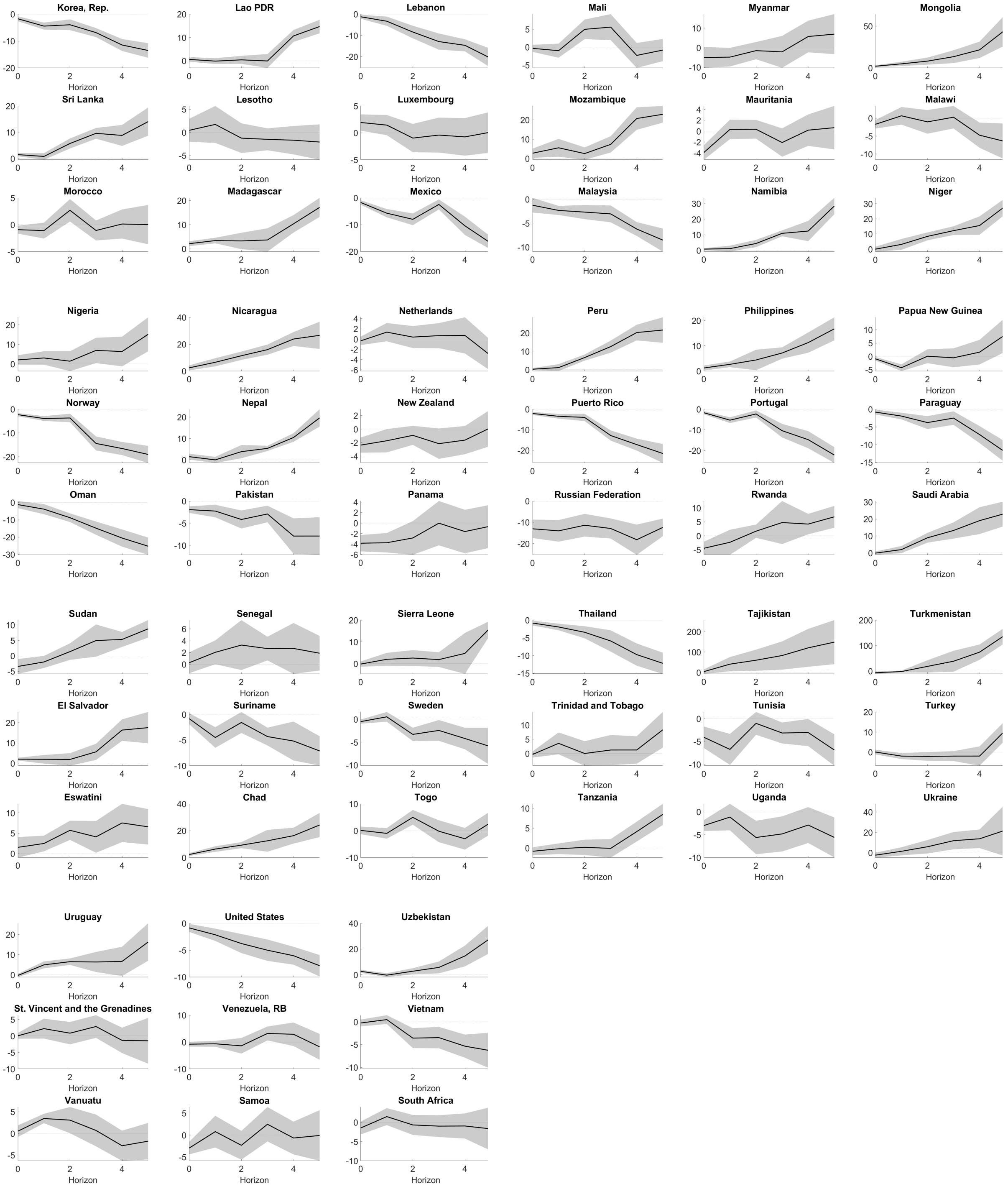
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D4: Global Temperature Pseudo-Panel Local Projection Impulse Responses


Angola
Albania
United Arab Emirates
Burkina Faso
Bangladesh
Bulgaria
Argentina
Australia
Austria
Bahamas, The
Belize
Bolivia
Burundi
Belgium
Benin
Brazil
Brunei Darussalam
Bhutan
Botswana
Central African Republic
Canada
Congo, Rep.
Colombia
Comoros
Switzerland
Chile
China
Cabo Verde
Costa Rica
Cuba
Cote d'Ivoire
Cameroon
Congo, Dem. Rep.
Cyprus
Germany
Denmark
Dominican Republic
Algeria
Ecuador
Gabon
United Kingdom
Georgia
Egypt, Arab Rep.
Spain
Ethiopia
Ghana
Guinea
Gambia, The
Finland
Fiji
France
Guinea-Bissau
Equatorial Guinea
Greece
Greenland
Guatemala
Guyana
Iraq
Iceland
Israel
Honduras
Haiti
Indonesia
Italy
Jamaica
Jordan
India
Ireland
Iran, Islamic Rep.
Japan
Kenya
Kyrgyz Republic

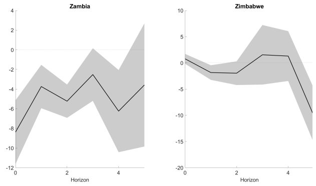
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D5: Global Temperature Pseudo-Panel Local Projection Impulse Responses (Continued)



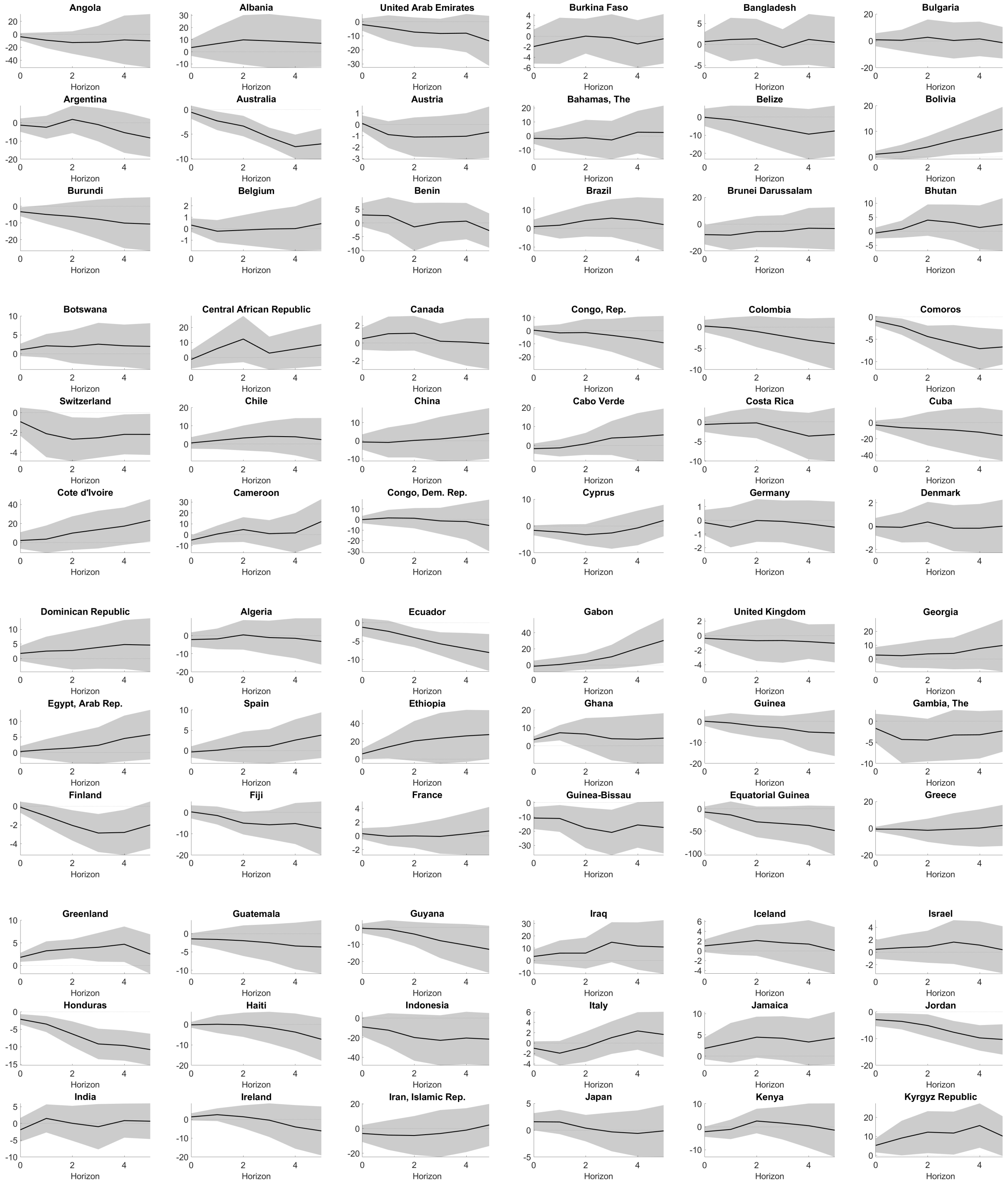
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D6: Global Temperature Pseudo-Panel Local Projection Impulse Responses (Continued)



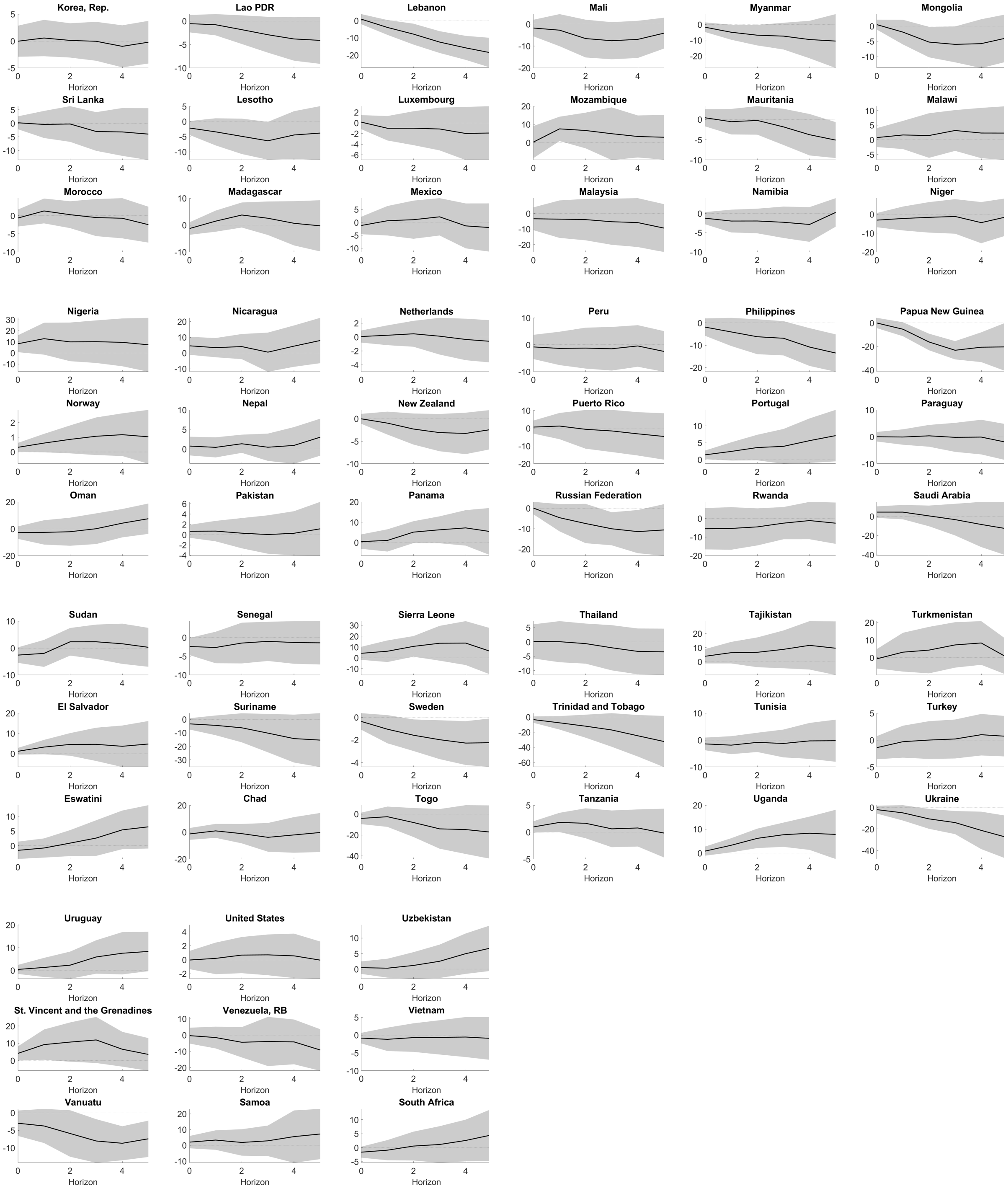
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D7: Idiosyncratic Temperature Local Projection Impulse Responses



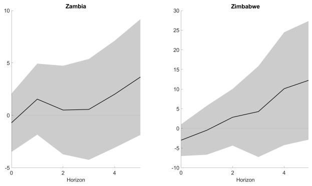
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D8: Idiosyncratic Temperature Local Projection Impulse Responses (Continued)



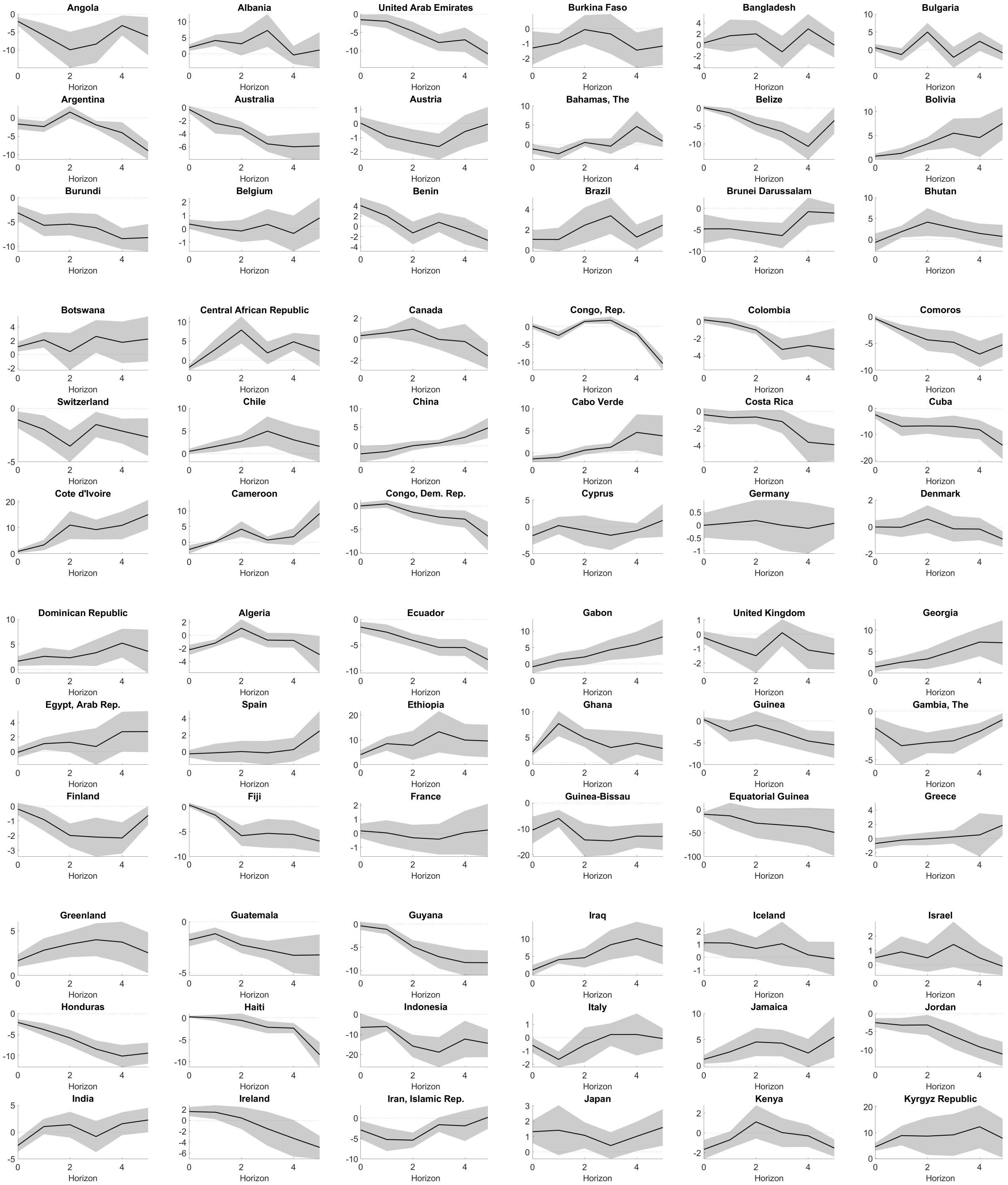
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D9: Idiosyncratic Temperature Local Projection Impulse Responses (Continued)



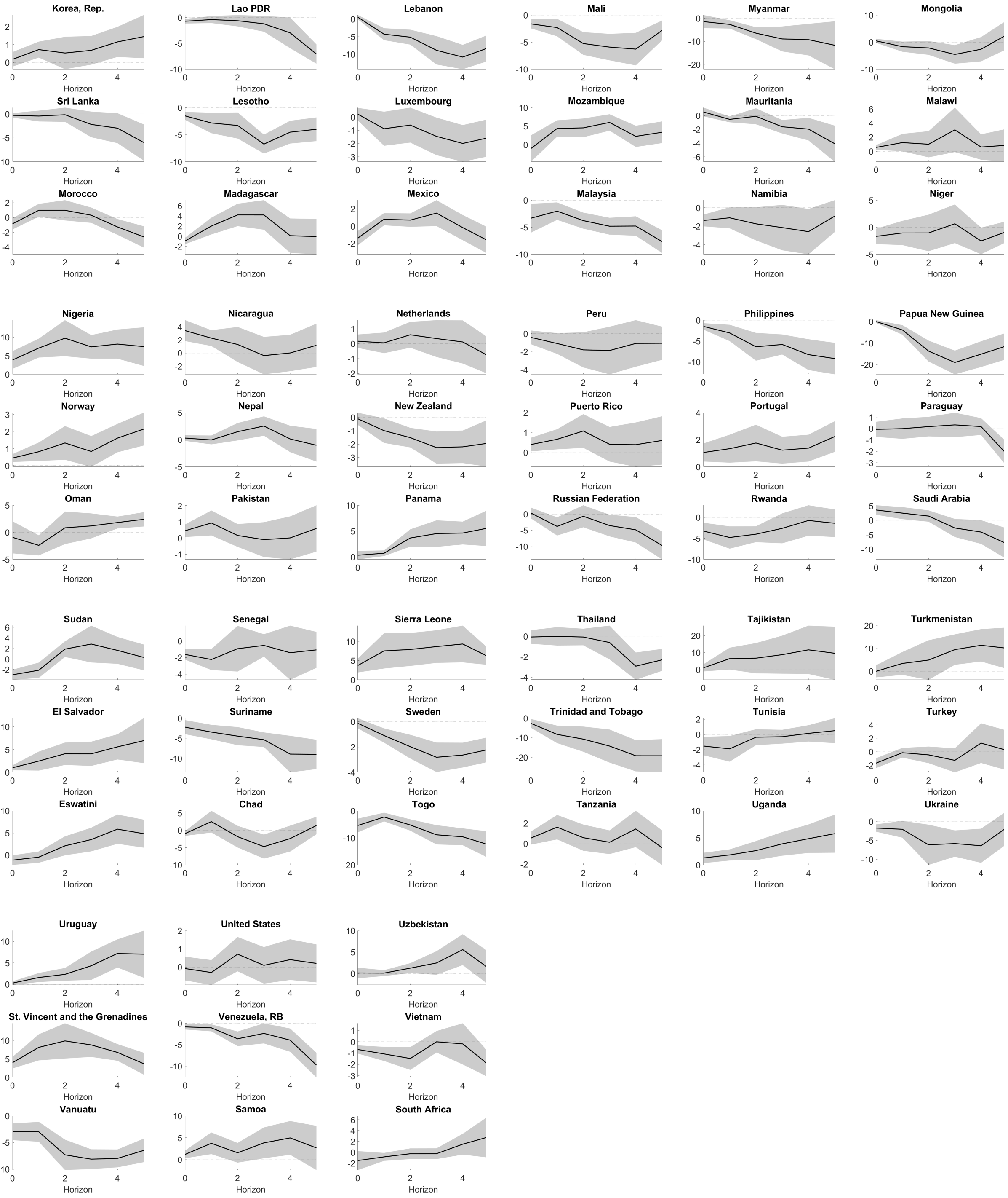
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D10: Idiosyncratic Temperature Pseudo-Panel Local Projection Impulse Responses



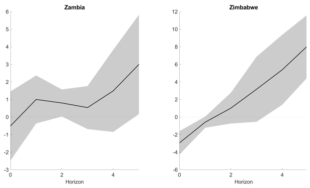
Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D11: Idiosyncratic Temperature Pseudo-Panel Local Projection Impulse Responses (Continued)



Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).

Figure D12: Idiosyncratic Temperature Pseudo-Panel Local Projection Impulse Responses (Continued)



Notes: Shaded areas are plus and minus 1.96 standard error bands. Specifications are determined by Akaike's Information Criterion (AIC).