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The Effect of Extreme Heat on Economic Growth:

Evidence from Latin America

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Abstract

Climate change is projected to increase the frequency and intensity of extremely hot days. We use a panel regression framework at the sub-national (i.e., region) level to identify the effect of extreme heat on economic growth in Latin America accounting for acclimation to the season and to the local climate. Extreme heat has a negative and significant impact on economic growth, and the magnitude of the impact is increasing in the intensity and duration of heat. Our results suggest that the impact of each additional consecutive day of extreme heat is greater than the impact of the prior day. Extreme heat affects economic growth directly in addition to its indirect effect through higher seasonal mean temperatures and extreme heat could account for 34-68% of the total projected reduction in the annual economic growth rate at mid-century due to temperature change. Our results suggest that extreme heat is one potential channel for the documented non-linearity in the impacts of rising mean temperature.

JEL Classification: Q5, Q54, Q51

Keywords: Extreme heat, Heat waves, Economic growth, Latin America

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1 Introduction

Climate change will increase mean annual and seasonal temperatures (IPCC, 2023), and a large literature documents a negative relationship between mean annual or seasonal temperature and economic activity (Dell et al., 2012; Burke et al., 2015; Colacito et al., 2019; Acevedo et al., 2020). However, climate change will also increase the variance of the temperature distribution (IPCC, 2023), leading to changes in temperature that are not well captured by changes in mean temperatures. If daily temperature has a bell-shaped distribution, then a small increase in the mean coupled with an increase in variance flattens the bell curve and shifts it rightward, leading to a large increase in the number of extremely hot days. These changes in the distribution of temperature imply that climate change will increase the intensity, duration, and frequency of heat waves (Wang et al., 2023; Coffel et al., 2017; Russo et al., 2014; Meehl and Tebaldi, 2004). Because extreme heat affects physical and cognitive performance (Tattersson et al., 2000; Chen et al., 2004; Cedeño Laurent et al., 2018; Graff Zivin et al., 2018; Park et al., 2020), heat waves could have a particularly large impact on economic activity.

We use a panel regression framework at the sub-national (i.e., region) level to identify the effect of extreme heat on economic growth in Latin America. Specifically, we use an unbalanced panel of region-level data on annual gross regional product (GRP) for 15 countries in Latin America from 1970 to 2010 from Gennaioli et al. (2014) together with hourly temperature, humidity, and precipitation data from ERA5 (Hersbach et al., 2023) aggregated to the region level. We identify the impact of extreme heat by exploiting plausibly exogenous changes in the count of hot days and heat waves across years and regions while controlling for mean seasonal temperatures. We define hot days as days

with maximum hourly heat index above given percentiles of the distribution of maximum daily heat index over the previous decade by region-month. We focus on region-calendar month specific measures of extreme heat because days with the same absolute level of the heat index may have different effects on economic growth in different regions or months of the year. In addition, by defining hot days relative to each region’s long-term moving historical distribution (i.e., local climate), our measures of hot days capture extreme heat for a given climate and calendar month while allowing the local climate to gradually evolve over the time period of our study. In this way, our measures of extreme heat account for acclimation to the season and to the local climate. We define a heat wave as consecutive hot days. We vary the percentile of the distribution used to define a hot day and the number of consecutive hot days used to define a heat wave to compare the effects of heat waves of different intensities and durations.

We document that extreme heat has an economically and statistically significant effect on economic growth. An additional day with heat index above the 85th percentile reduces the growth rate of GRP by 0.007 percentage points. This effect increases, generally non-linearly, with the percentile of the distribution at which we define a hot day. For instance, an additional day with heat index above the 91st percentile reduces the growth rate of GRP by 0.010 percentage points and an additional day with heat index above the 97th percentile reduces the growth rate of GRP by 0.022 percentage points.

Next, we explore the effect of heat waves. We find that the magnitude of the negative impact is increasing in both the intensity and the duration of the heat wave. For instance, a heat wave of at least 7 days above the 85th percentile reduces the growth rate of GRP by 0.135 percentage points, while a heat wave of at least 7 days above the 91st percentile reduces the growth rate of

GRP by 0.264 percentage points, and a heat wave of at least 7 days above the 97st percentile reduces the growth rate of GRP by 0.579 percentage points. Similarly, a heat wave of at least 1 day with maximum hourly heat index above the 97th percentile reduces the growth rate of GRP by 0.026 percentage points, while at least 3 consecutive days reduces the growth rate of GRP by 0.146 percentage points, and at least 7 consecutive days reduces the growth rate of GRP by 0.579 percentage points. Generally, the effects are increasing non-linearly in both the intensity and the duration. For example, the impact of at least one day with maximum heat index above the 97th percentile has an impact 1.9 times that of a day in the 91st percentile while a heat wave of at least 3 consecutive days above the 97th percentile has an impact 9.9 times that of 3 consecutive days above the 91st percentile. These results suggest that consecutive days of extreme heat have different effects on economic growth than dispersed days of extreme heat.

The magnitude of the effects of hot days and heat waves are economically meaningful. In a typical year in the sample, for instance, the growth rate of economic output for the region of São Paulo, Brazil, is reduced by 0.368 percentage points by the days with a maximum heat index above the 97th percentile (top 3 percent) of the month’s distribution. Considering heat waves, the growth rate of economic output in the region of São Paulo is reduced by 0.282 percentage points due to heat waves of at least 3 consecutive days above the 97th percentile in a typical year in our sample. Our primary findings that extreme heat reduces economic growth and that the magnitude of the effect is increasing in the intensity and duration of heat are consistent and robust across numerous alternative specifications.

To provide a ballpark estimate of the impact of extreme heat on economic growth as the climate changes, we combine our coefficients estimated in the

historical data with projections for the increase in the number of hot days and heat waves in 2046-2055 from Feron et al. (2019). This back-of-the-envelope estimate suggests that the negative effects of extreme heat on the growth rate of economic activity will increase. For instance, São Paulo is projected to experience a reduction in the annual growth rate of GRP of 2.1 percentage points in 2046-2055 due to an increase in the number of heat waves with at least 3 consecutive days with heat index above the 97th percentile.

Our results have two broader implications for adaptation to climate change. First, the significant negative impact of extreme heat that we find illustrates that economic activity is vulnerable to extreme heat. Adapting economic activity to extreme heat is challenging because, similar to other extreme weather events, heat waves are relatively infrequent, intense, and difficult to predict in advance.

Second, our results demonstrate that extreme heat significantly impacts economic growth beyond its effects through average seasonal or annual temperature. Furthermore, our results suggest that the negative impacts of extreme heat constitute a large share of the negative impacts of changes in temperature due to climate change. We combine our estimated coefficients for the impact of seasonal mean temperatures and of extreme heat with climate projections to mid-century from the IPCC (2023) and Feron et al. (2019). Across the 14 regions considered, the impact of extreme heat (days above the 97th percentile) accounts for 34-68% of the total effect of temperature changes. This finding is consistent with other studies documenting that the economic costs of climate change will be caused primarily by extreme weather events (events in the tails of the distribution) rather than slow-moving changes in means (Newman and Noy, 2023; Bilal and Känzig, 2024). Integrated Assessment Models focus on the economic impacts of changes in average temperature and generally ignore

extreme events (Newman and Noy, 2023). We provide additional evidence that ignoring extreme events leads to an underestimation of the economic impacts of climate change and that adapting to extreme heat is important for reducing the negative impact of changes in temperature due to climate change.

We build on the prior literature documenting links between the economy and weather and climate. Several studies document that extreme heat has a negative impact on aggregate agricultural output (Schauberger et al., 2017; Annan and Schlenker, 2015; Massetti and Mendelsohn, 2015; Roberts and Schlenker, 2010; Schlenker and Roberts, 2009), but the effects of extreme heat on aggregate economic output has received little attention despite several studies documenting that high temperature has a negative impact on labor supply and labor productivity (Heyes and Saberian, 2022; Behrer et al., 2021; Somanathan et al., 2021; Orlov et al., 2019; Zhang et al., 2018; Zander et al., 2015; Graff Zivin and Neidell, 2014). Miller et al. (2021) begins to bridge this gap by using a measure of prolonged exposure to heat in a country-year panel to estimate the impact of heat waves on national agricultural output and on GDP.

This paper makes two main contributions to the literature studying the effects of extreme heat on aggregate economic activity. First, our results illustrate that the negative effect of extreme heat on aggregate economic growth is increasing in both the intensity and duration of extreme heat. We use easy-to-interpret measures of extreme heat that allow for comparison across heat waves of different intensity and duration. Second, our results provide additional evidence that the negative economic impacts of rising temperature will primarily be due to extreme events rather than a gradual increase in local mean temperatures.

This paper complements the literature documenting the effects of mean an-

nual and seasonal temperatures on aggregate economic growth. Our results are consistent with studies documenting non-linearities in the economic impacts of rising temperature (Schlenker and Roberts, 2006, 2009; Burke et al., 2015) and provide evidence suggesting that extreme heat is one potential channel driving these non-linearities.

2 Data

We use annual per-capita gross regional product (GRP) as a measure of economic activity at the region level (highest sub-national administrative level) from Gennaioli et al. (2014). We use a sub-national level of aggregation to avoid spatially aggregating weather across large geographies, which is important because many nations in our sample span large geographic areas with various local climates. These data contain an unbalanced panel of 15 Latin American countries from 1970 to 2010. Specifically, the 15 countries in our sample are Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Peru, Uruguay, and Venezuela. Chile, Ecuador, Honduras, Nicaragua, and Venezuela have economic data for a subset of their regions. The per-capita GRP is in current purchasing power (\$US).¹ We winsorize the annual GRP growth rates at the 1st and 99th percentiles resulting in a range of GRP growth rates of -18.53 to 21.43. This range is similar to the range of local currency GDP growth rates for these 15 countries over the period 1970-2010 in the World Bank World Development Indicators (-26.48 to 18.29) (World Bank, 2024)

We merge the economic data with weather data from ERA5 at the region

¹Gennaioli et al. (2014) convert GRP data into per-capita (current purchasing power) US\$ values by multiplying national GDP in PPP terms by each region’s share of national GDP and then dividing by the regional population.

level, with a few exceptions in Brazil, Peru, and Colombia. As described in the Data Appendix, there are some regions in these countries that are aggregated together in the economic data. In these cases, we aggregated the weather data to the level of the economic data. Appendix Table A1 describes the number of region-year observations in the sample for each country. In the case of Nicaragua, before aggregating the weather data to the region level, we aggregated the geospatial data to the level below the highest sub-national administrative level using area weighted averages.

We use hourly temperature (degrees Celsius), humidity, and precipitation data from ERA5 (Hersbach et al., 2023),² which provides time series reanalysis data at a high spatial resolution (0.25 degree x 0.25 degree grid cells). We use geospatial data from the Database of Global Administrative Areas (GADM, 2012) to aggregate the ERA5 gridded data to the region level by computing area-weighted averages. GADM is a high-resolution database of administrative areas that seeks to provide spatial data for all countries and sub-divisions. We use information on administrative borders at the highest-level below the nation state (level 1) to map ERA5 grid cells to administrative units.

We use the hourly heat index to create our measures of extreme heat because the heat index combines temperature and relative humidity to represent how weather conditions feel to the human body. We compute relative humidity as in Alduchov and Eskridge (1996), and then we compute the heat index as in Anderson et al. (2013) following the procedure of the National Weather Service.³ The heat index has a direct relationship with air temperature and relative humidity in which the heat index rises with increases in air tempera-

²ERA5 is the fifth generation reanalysis for the global climate and weather for the past 8 decades from the European Centre for Medium-Range Weather Forecasts (ECMWF).

³https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml

ture and/or relative humidity. Appendix Figure A1 shows the distributions of the hourly heat index and the mean daily heat index.

We create several sets of variables for the empirical analysis. First, we create summary measures of the heat index and precipitation. We create variables for the annual mean heat index and seasonal mean heat index. We define seasons as January - March (summer), April - June (fall), July - September (winter), October - December (spring) for countries in the Southern Hemisphere. We reverse the definition of seasons for El Salvador, Guatemala, Honduras, Mexico, and Panama because they are located in the Northern Hemisphere.

Second, we use bins of the heat index distribution to investigate the impact of temperature on economic growth across the full distribution. We create two sets of five variables representing the annual count of days or hours that fall into each bin of the mean daily heat index distribution and of the hourly heat index distribution. For the mean daily heat index, bin 1 contains up to 7C, bin 2 ranges from 7C up to 14C, bin 3 ranges from 14C up to 21C, bin 4 ranges from 21C up to 28C, and bin 5 contains 28C and above. Because the mean daily heat index averages out the extreme values of the distribution of hourly heat index, the range of the hourly heat index is wider than that of the daily mean heat index. Therefore, for the hourly heat index, bin 1 contains up to 5C, bin 2 ranges from 5C up to 14C, bin 3 ranges from 14C up to 23C, bin 4 ranges from 23C up to 32C, and bin 5 contains 32C and above.

Third, we create sets of variables that focus on extreme heat. To investigate the effect of hot days, we create the annual count of days in which the maximum of the hourly heat index is above specific percentiles of the distribution of daily maximum heat index over the prior decade by region-month. We gradually increase the threshold used to define a hot day from the 15th percentile of the distribution to the 1st percentile of the distribution to inves-

tigate the impact of increasing heat intensity. Appendix Table A2 shows there is significant variation in the number of hot days across countries.

These measures of extreme heat relative to the region-month specific moving distribution account for acclimation to the season and to the local climate. The broad geographic scope of our study implies that the same absolute level of the heat index may have different effects on economic growth in different regions or months of the year. In contrast, our relative measures of hot days consistently capture unusually hot days for a given climate and calendar month while allowing the local climate to gradually evolve over the time period of our study.

Our measure of hot days ignores the timing of hot days. Because consecutive hot days may be more detrimental to economic growth than dispersed hot days, we investigate the effect of heat waves. We define a heat wave as consecutive hot days. We gradually increase the number of consecutive days used to define a heat wave from at least 1 single day to at least 7 consecutive days to investigate the impact of increasing duration of heat. Specifically, for each level of heat intensity (15th to 1st percentile), we create the annual count of heat waves of each duration (at least 1 single day to at least 7 consecutive days) and level of heat intensity (15th to the 1st percentile of the distribution of heat index) in our sample. The number of heat waves is decreasing in both the intensity and the duration, reflecting that more extreme heat waves are less frequent.

To calculate a back-of-the-envelope estimate of the impact of extreme heat at mid-century, we use climate projections from Feron et al. (2019). We use projections of the number of heat waves by mid-century (2046-2055) and the increase in the share of hot days by mid-century (2046-2055) compared to the

baseline period 1961-1990 for 14 Latin American cities from Feron et al. (2019). The projections in Feron et al. (2019) are based on the RCP 4.5 scenario and the Regional Climate Models (RCMs) from the Coordinated Regional Climate Downscaling Experiment (CORDEX) for South America. Their definitions of hot days and heat waves differ slightly from the ones that we use in the historical weather data. In Feron et al. (2019), a heat wave is defined as a period of at least three consecutive days with daily maximum temperatures exceeding a threshold calculated for each location (or climate model grid point) using the 95th percentile of the daily maximum temperature anomaly distribution over a base period.

To quantify the impact of extreme heat relative to the overall effect of temperature changes by mid-century, we additionally use seasonal mean temperature projections from the IPCC Atlas (Gutiérrez et al., 2021). This dataset employs CMIP6 model projections under the SSP2-4.5 scenario, providing projected changes in seasonal mean temperatures for the two-decade period 2041-2060 compared to the baseline period 1981-2010. The definition of seasons is consistent with our definition in the historical weather data. Since the IPCC data are aggregated to subregions that differ from the first subnational level of aggregation in the economic data, we extract the IPCC data and match our spatial resolution by averaging the projections.

Using the projections for changes in extreme heat and seasonal temperature by mid-century, we construct a ratio that captures the impact of extreme heat relative to the total effect of temperature changes. The numerator is the coefficient of extreme heat from the empirical analysis multiplied by the increase in extreme heat—i.e., the average number of hot days or heatwaves in our historical data (ERA5) times the projected increase factor according to (Feron et al., 2019). The denominator is the sum of the numerator and

the products of the coefficients of the seasonal mean temperatures from the empirical analysis and the corresponding projected seasonal changes from the IPCC Atlas. We focused on four definitions of extreme heat: top 3% hot days, top 5% hot days, heat waves of at least 3 days of top 3% hot days, and heat waves of at least 3 days of top 5% hot days.

3 Empirical Strategy

We estimate panel regressions at the region-year level with region and year fixed effects to control for time-invariant determinants of economic growth within a region and determinants of economic growth that are common across regions within a year. This allows us to isolate the effect of plausibly exogenous changes in the heat index across regions and years on economic growth.

In the first specification, we estimate the effect of annual heat index on the annual growth rate of GRP.

$$\Delta y_{i,t} = \alpha + \beta T_{i,t} + \gamma_i + \nu_t + \sum_{m=1}^{12} \eta_m p_{i,m,t} + \lambda \Delta y_{i,t-1} + \epsilon_{i,t} \quad (1)$$

$\Delta y_{i,t}$ is the growth rate of per capita GRP in region i between year t and $t - 1$, and $T_{i,t}$ is the annual mean heat index in region i in year t . γ_i and ν_t denote region and year fixed effects. $p_{i,t}$ is mean precipitation in region i in month m of year t , and $\Delta y_{i,t-1}$ is the lagged growth rate of GRP in region i , i.e., the growth rate of GRP in region i between year $t - 1$ and $t - 2$. Because growth rates of GRP are autocorrelated, we include the lagged dependent variable to control for autocorrelation in economic growth rates.⁴ We cluster standard errors by region.

⁴We also demonstrate that our main results are robust to the exclusion of the lagged dependent variable to avoid the Nickell bias (Nickell, 1981).

In the second specification, we replace the annual mean heat index in equation (1) with five bins that contain the annual count of days or hours in each range of the mean daily heat index or hourly heat index.

$$\Delta y_{i,t} = \alpha + \sum_{k=1,2,4,5} \beta_k B_{i,t,k} + \gamma_i + \nu_t + \sum_{m=1}^{12} \eta_m p_{i,m,t} + \lambda \Delta y_{i,t-1} + \epsilon_{i,t} \quad (2)$$

We omit the third (middle) bin so we interpret the coefficients on the other four bins relative to the third bin. In particular, the coefficient β_k is an estimate of the effect of replacing a day or hour with heat index in the third bin with a day or hour with heat index in the k^{th} bin on the annual GRP growth rate.

In the third specification, we replace annual mean heat index in equation (1) with the annual count of hot days of a specific intensity or the annual count of heat waves of a specific intensity and duration. We estimate a separate regression for each combination of intensity and duration.

$$\Delta y_{i,t} = \alpha + \beta C_{i,t} + \gamma_i + \nu_t + \sum_{m=1}^{12} \eta_m p_{i,m,t} + \sum_{s=1}^4 \phi_s T_{i,s,t} + \lambda \Delta y_{i,t-1} + \epsilon_{i,t} \quad (3)$$

where $C_{i,t}$ is the count of hot days of a specific intensity or heat waves of a specific intensity and duration in region i in year t and $T_{i,s,t}$ is the mean temperature in region i in season s in year t . An extremely hot day will increase the average seasonal temperature, which affects economic growth. Therefore, we also control for seasonal mean temperatures to isolate the direct effect of extreme heat on economic growth.⁵

⁵The range of correlations between our measures of hot days or heat waves and seasonal

4 Results

4.1 Impact of Heat on Economic Growth

We begin by documenting that the annual mean heat index has a negative impact on economic growth. Column (1) of table 1 shows that the effect is economically and statistically significant. A 1 degree Celsius increase in the mean annual heat index is associated with a reduction in the annual GRP per capita growth rate of 0.693 percentage points. This result is in line with estimates of the impact of mean temperature from other studies. For example, Colacito et al. (2019) find that a 1 degree Fahrenheit increase in mean summer temperature in the Southern region of the United States is associated with a reduction in the growth rate of gross state product of 0.326 percentage points, which implies a reduction of 0.587 percentage points for a 1 degree Celsius increase in mean summer temperature. Our estimate is 18% larger than that for the mean summer temperature in Colacito et al. (2019), which could be due to different climates, economic sector compositions of GRP, or levels of development (Burke et al., 2015; Colacito et al., 2019; Acevedo et al., 2020).

Next, we look at the effect of the heat index on economic growth across the full distribution of the heat index. We find that the negative effects of the mean annual heat index are driven by the hottest temperatures. Column (2) presents the results using annual counts of days with mean daily heat index in a set of bins. Replacing a day with mean heat index between 14C and 21C (the reference bin) with a day with mean heat index less than 7C has an insignificant effect on the growth rate of GRP and replacing a day in the reference bin with a day with mean heat index between 7C and up to 14C has

temperatures is 0.05 to 0.2.

a small positive impact on the growth rate of GRP. In contrast, replacing a day in the reference bin with a hotter day with mean heat index between 21C to 28C is associated with a reduction in the growth rate of GRP per capita of 0.015 percentage points, and replacing a day in the reference bin with a hotter day with mean heat index above 28C is associated with a reduction in the GRP per capita growth rate of 0.035 percentage points. Column (3) presents the results using bins of the hourly heat index. The heat index thresholds that define the hourly bins differ slightly from those that define the daily bins because the distribution of hourly heat index is wider than the distribution of daily mean heat index. While the magnitude of the coefficients is smaller than those of the bins of the daily mean heat index because they represent the impact of an hour instead of a day, the pattern is very similar. Replacing an hour in the reference bin (14C to 23C) with an hour below 5C or an hour between 5C and 14C is associated with an increase in the growth rate of GRP per capita of 0.001 percentage points. In contrast, replacing an hour in the reference bin with an hour with heat index between 23C and 32C and with an hour above 32C is associated with a reduction in the growth rate of GRP per capita of 0.001 and 0.003 percentage points. These results are robust to using annual mean temperature and bins of the daily mean and hourly temperature (degrees Celsius) (columns (4)-(6)).⁶

Motivated by these findings, we focus on the impact of extreme heat on economic growth. Figure 1 illustrates that hot days have a significant negative effect on economic growth and that the magnitude of the impact is increasing in the intensity of the heat.⁷ A day with maximum heat index above the 85th percentile of the distribution of maximum heat index for the region-month

⁶These results are robust to numerous specifications (see Appendix tables A3 - A6).

⁷Coefficients and standard errors are shown in Appendix table A7.

reduces the growth rate of per capita economic output by 0.007 percentage points. In comparison, a day above the 91st percentile reduces the growth rate of per capita economic output by 0.010, a day above the 97th percentile reduces the growth rate of per capita economic output by 0.022, and a day above the 99th percentile reduces the growth rate of per capita economic output by 0.038. The magnitude of the effects is economically meaningful. For instance, considering the average number of hot days for the region of São Paulo, Brazil in our sample, the growth rate of per capita economic output for the region of São Paulo, Brazil is reduced by 0.368 percentage points by days with a maximum heat index in the 97th percentile (top 3 percent). The effects are even larger in regions with more hot days.

Our results are robust to winsorizing the GDP growth rate at the 5th and 95th percentiles (see Appendix Figure A3) and to numerous alternative specifications. Our results are robust to including linear and quadratic region trends (see Appendix Figure A4), controlling for annual mean temperature instead of seasonal mean temperature (see Appendix Figure A5), and excluding the lagged per capita GRP growth rate (see Appendix Figure A6). We find qualitatively similar results when including country by year fixed effects instead of sets of region and year fixed effects, but the coefficients are smaller in magnitude and less precise since the country by year fixed effects absorb much of the variation that contributes to identification (see Appendix Figure A7). We also find consistent results when including the local currency-USD real exchange rate to control for changes in relative prices (see Appendix Figure A8).

Our results are also robust to different relative definitions of hot days. We define hot days using percentiles of the distribution of the heat index over 1960-1969 (prior to the period of analysis) by region-month. In general, the region-month heat index distributions have shifted slightly rightward from

1960 to 2010, implying that defining hot days relative to the moving distributions captures hotter days. Appendix Figure A9 shows that the results are consistent with those in Figure 1. In comparison to figure 1, the effects appear slightly smaller in magnitude at higher thresholds, which is consistent with other evidence that the magnitude of the effect is increasing in the intensity of heat. We also define hot days as the product of our main hot days variable and an indicator for whether the average of the daily maximum heat index by region-month in 1960-1969 is above 28C. This indicator varies at the region-calendar month level, so it is constant across years of the sample. Appendix Figure A10 shows that we obtain quantitatively similar results using this measure of hot days. Appendix Figure A11 illustrates that the results are quantitatively very similar when defining hot days using temperature and the moving distribution of temperature by region-month instead of the heat index. Finally, our results are robust to defining hot days according to thresholds defined in terms of standard deviations above the mean of the maximum daily heat index distribution over the previous decade by region-month (See Appendix Figure A12).

In addition, our results are robust to using an absolute measure of hot days. In contrast to the prior measures of hot days that are defined relative to the distribution of the heat index or temperature by region-month, absolute measures of hot days are defined using absolute thresholds of the heat index. The relative measures of hot days capture days that are comparatively unusual across locations and calendar months relative to the recent local climate but may differ substantially in terms of the level of the heat index or temperature. The absolute measures of hot days capture days that have comparable levels of the heat index across regions and calendar months but the extent to which this level of the heat index is unusual may differ substantially across regions and

calendar months. Appendix Figure A13 shows that we find a similar pattern of negative effects of absolutely hot days on economic growth with coefficients that generally increase in magnitude with the threshold at which we define a hot day.

Next, we estimate the effect of heat waves on economic growth because consecutive hot days could have different effects than disparate hot days throughout the year. Figure 2 shows that heat waves have a negative effect on the growth rate of economic output and that the magnitude of the effect is increasing in the intensity and duration of heat.⁸ For instance, a heat wave of at least 7 consecutive days above the 85th percentile reduces the growth rate of GRP per capita by 0.135 percentage points, while a heat wave of at least 7 days above the 91st percentile reduces the growth rate of GRP per capita by 0.264 percentage points, and a heat wave of at least 7 days above the 97th percentile reduces the annual growth rate of GRP per capita by 0.579 percentage points. Similarly, a heat wave of at least 1 day with maximum hourly heat index above the 97th percentile reduces the growth rate of GRP per capita by 0.026 percentage points, while at least 3 consecutive days reduces the growth rate of GRP per capita by 0.146 percentage points, and at least 7 consecutive days reduces the growth rate of GRP per capita by 0.579 percentage points. The results imply that higher intensity and duration heat waves have substantially larger effects. For instance, the impact of at least one day with maximum heat index above the 97th percentile has an impact 1.9 times that of a day in the 91st percentile, and a heat wave of at least 3 consecutive days above the 97th percentile has an impact 9.9 times that of 3 consecutive days above the 91st percentile.

Generally, the magnitude of the effect of extreme heat is increasing non-

⁸Appendix Table A8 shows the coefficients and standard errors.

linearly in both the intensity and the duration. We explore non-linearity in the duration of extreme heat by dividing the heat wave coefficient by the minimum duration of the heat waves to generate an estimate of the per day effect of a heat wave. Figure 3 plots the results. Particularly for more intense heat waves, such as those above the 97th percentile, the negative per day effect of a heat wave is increasing in the number of consecutive days in the heat wave. For instance, the first day of a heat wave above the 97th percentile reduces the growth rate of GRP per capita by 0.026 percentage points, while the seventh consecutive day reduces the growth rate of GRP per capita by 0.083 percentage points. These results suggest that each successive day of extreme heat has a greater effect on economic growth than the previous.

Our results documenting the impacts of heat waves are robust to winsorizing the GDP growth rate at the 5th and 95th percentiles (see Appendix Figure A14) and numerous alternative specifications such as including linear and quadratic region trends (see Appendix Figure A15), controlling for annual mean temperature instead of seasonal mean temperatures (see Appendix Figure A16), excluding the lagged growth rate of GRP per capita (see Appendix Figure A17), including country by year fixed effects (see Appendix Figure A18), and controlling for the real exchange rate (see Appendix Figure A19).

Our results are also robust to different relative and absolute definitions of heat waves. Appendix Figure A20 shows a consistent pattern of effects when defining heat waves using percentiles of the distribution of the heat index over 1960-1969 (prior to the period of analysis) by region-month. Similar to hot days, in comparison to Figure 2, the magnitude of the effects appears smaller for more extreme combinations of intensity and duration likely because the thresholds defined by given percentiles of the moving distributions has generally increased over time. Appendix Figure A21 shows that our results are

robust to defining heat waves as the product of our main heat waves measure and the indicator for hot region-month. Appendix Figure A22 illustrates that the results are quantitatively very similar when defining heat waves using temperature and the moving distribution of temperature instead of the heat index. Our results are also robust to defining heat waves according to thresholds defined in terms of standard deviations above the mean of the maximum daily heat index distribution over the previous decade by region-month (See Appendix Figure A23). Finally, Appendix Figure A24 shows a similar pattern of negative effects of heat waves defined using absolute thresholds of the heat index in degrees Celsius on economic growth with coefficients that generally increase in magnitude with the intensity and duration of the heat wave.

4.2 Combining Impacts with Climate Projections

In this section, we present back-of-the-envelope estimates for the projected change in annual per capita economic growth by mid-century due to changes in extreme heat under the RCP 4.5 scenario using the coefficients estimated in the historical data and projections for extreme heat from Feron et al. (2019). Feron et al. (2019) present projections for the share of hot days and the number of 3-day heat waves above the 95th percentile for 14 cities that correspond to 14 regions in our sample.⁹ In particular, our back-of-the-envelope estimate is the product of the coefficient of the variable capturing the annual count of hot days or heat waves above the 95th or 97th percentile from Figures 1 and 2 and the projected increase in hot days or heat waves above the 95th percentile by

⁹The definitions of heat waves and hot days in Feron et al. (2019) differs slightly from ours. They define a heat wave as a period of at least three consecutive days in which the daily maximum temperature exceeds a location-specific threshold. This threshold is derived from the 95th percentile of the daily maximum temperature anomaly distribution for the base period of 1961-1990.

2046-2055.¹⁰

Figure 4a plots the back-of-the-envelope estimate for each region.¹¹ The regions are ordered from coolest to hottest along the x-axis according to mean temperature for 1970-2010. Overall, hot days have a larger effect on the growth rate of GRP than heat waves because they are projected to increase by a greater factor. The change in the number of hot days relative to 1970-2010 defined by the 97th percentile are projected to reduce the annual growth rate of GRP per capita by 0.5-5.1 percentage points in 2046-2055, with the median regions projected to experience a reduction in the annual growth rate of GRP of 2.0 percentage points.¹² In comparison, the change in the number of 3-day heat waves of the same intensity is projected to reduce the annual growth rate of GRP per capita by 0.4-2.1 percentage points in 2046-2055, with the median regions projected to experience a reduction in the annual growth rate of GRP per capita of 1.1 percentage points.¹³

Next, we compute a back-of-the envelope calculation for the share of the total impact of temperature changes on the growth rate of GRP that is due to changes in extreme heat by mid-century. The share is computed as a ratio. The numerator is the projected reduction in the growth rate of GRP per capita due to changes in extreme heat (shown in Figure 4a), and the denominator is the numerator plus the coefficient of each seasonal mean temperature multiplied by the projected change in seasonal mean temperatures. We use projections for changes in seasonal mean temperature by 2041-2060 under the SSP2-4.5 scenario from Gutiérrez et al. (2021).

¹⁰We compute the factor by which Feron et al. (2019) predict that hot days and heat waves will increase in each region and multiply this factor by the historical average number of hot days and heat waves annually.

¹¹The project impacts displayed in Figure 4a are shown in Appendix Table A9

¹²The median regions are São Paulo, Brazil and Guayas, Ecuador.

¹³The median regions are Cundinamarca, Colombia and Caracas, Venezuela.

Figure 4b illustrates that extreme heat accounts for a substantial share of the reduction in economic growth due to temperature changes by mid-century. Projected increases in the number of hot days above the 97th percentile account for 34-68% of the reduction in annual economic growth, with the median regions' shares projected as 47% and 54%.¹⁴

These back-of-the-envelope calculations need to be interpreted with caution. They assume that the impact of extreme heat and seasonal mean temperatures on economic growth do not change over the time period under consideration and do not vary across geographies. They also ignore uncertainty about the point estimates of the estimated coefficients used in the exercise.

5 Conclusion

In this paper, we document that extreme heat has a negative and significant impact on economic growth and that the magnitude of the impact is increasing in the intensity and duration of heat. Our results suggest that the impact of each additional consecutive day of extreme heat is greater than the impact of the prior day. Extreme heat affects economic growth directly in addition to its indirect effect through higher seasonal mean temperatures, and extreme heat could account for 34-68% of the total projected reduction in the annual economic growth rate at mid-century due to temperature change. Because our measures of extreme heat account for acclimation to the season and to the local climate, our results highlight that adapting economic activity to extreme heat is challenging.

Our results are consistent with studies documenting non-linearities in the economic impacts of rising temperature (Schlenker and Roberts, 2006, 2009;

¹⁴The median regions are Santa Fe, Argentina and Santa Cruz, Bolivia.

Burke et al., 2015) and provide evidence suggesting that extreme heat is one potential channel driving these non-linearities.

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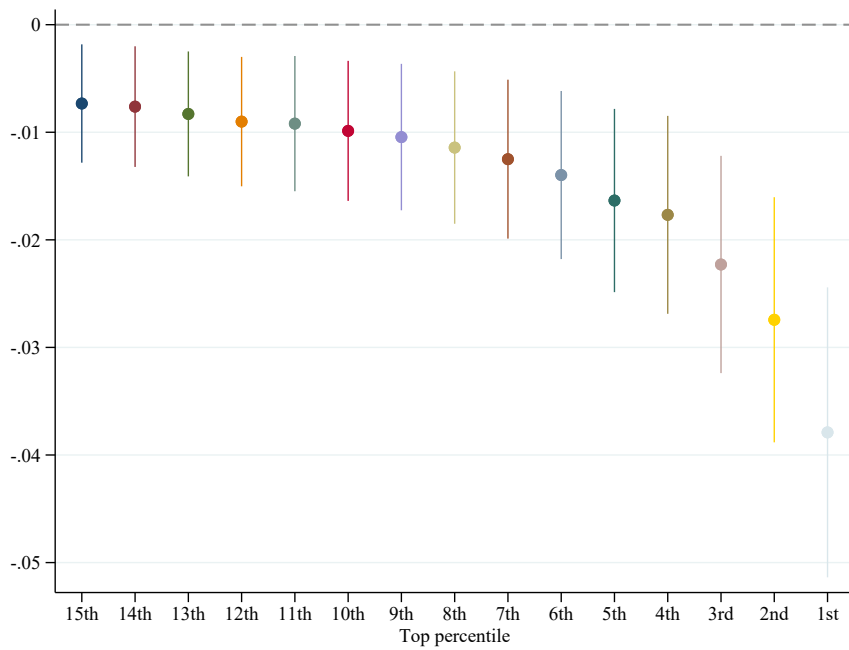
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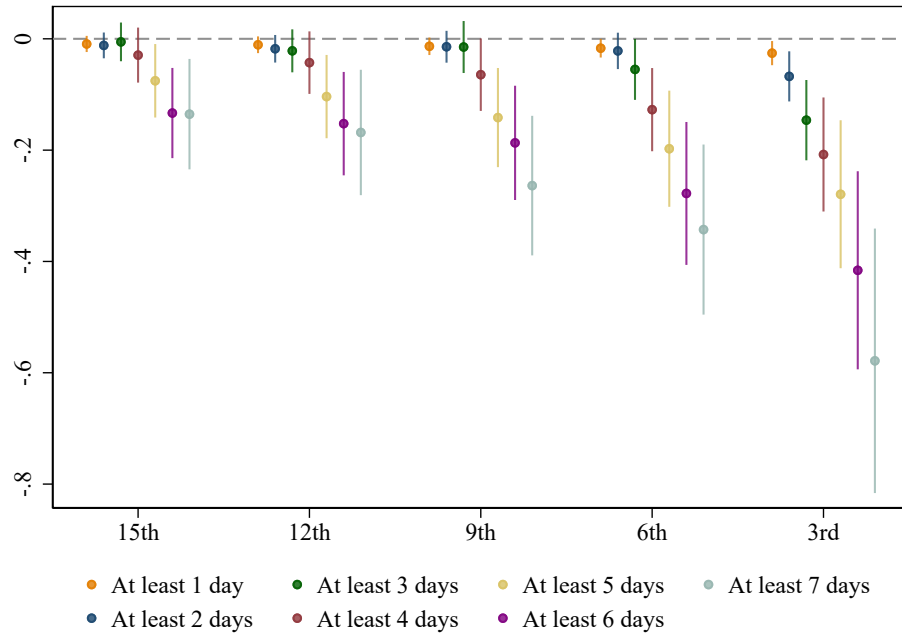
Figures

Figure 1: Effect of Hot Days on the Growth Rate of GRP



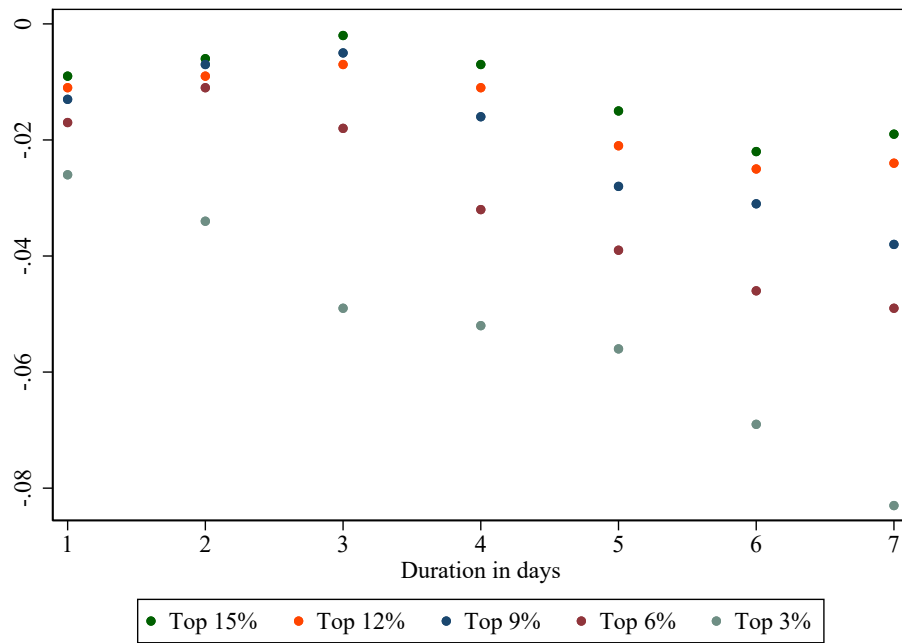
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Figure 2: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration



Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

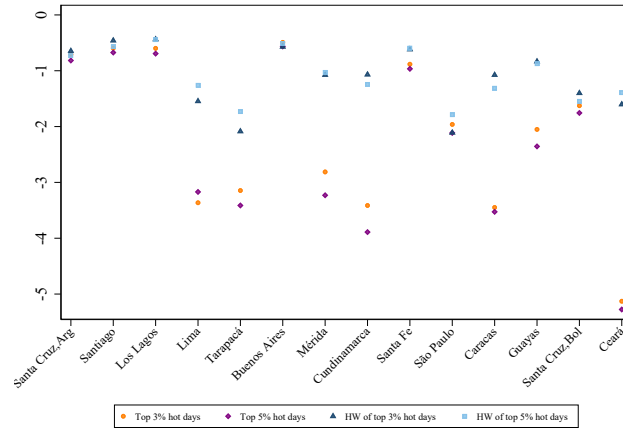
Figure 3: Effects of Heat Waves Per Day on the Growth Rate of GRP by Intensity and Duration



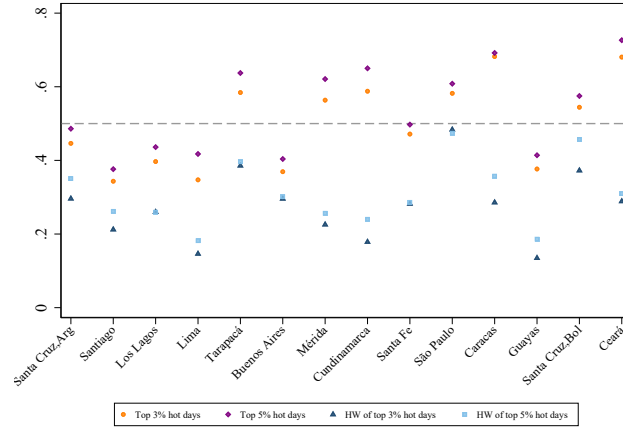
Notes: Each dot represents the coefficient of the count of heat waves of a given intensity and duration divided by the minimum duration of a heat wave (in days). Each coefficient is from a separate regression of the count of heat waves on the growth rate of per capita GRP. The duration of the heat wave is the minimum number of consecutive hot days required to constitute a heat wave.

Figure 4: Projected Impact of Additional Hot Days and Heat Waves (Defined by Heat Index) on the Growth of GRP at Mid-Century

(a) Projected change in the growth rate of GRP due to changes in extreme heat



(b) Share of the total impact of temperature changes



Notes: Panel A illustrates the projected change in the growth rate of GRP due to changes in extreme heat by mid-century. Panel B illustrates the share of the total impact of temperature changes by mid-century on the growth rate of GRP that is due to changes in extreme heat. Projections for regional changes in hot days and heat waves by 2046-2055 under the RCP 4.5 scenario are from Feron et al. (2019) and projections for changes in seasonal mean temperatures by 2041-2060 under the SSP2-4.5 scenario are from Gutiérrez et al. (2021). In Panel A, the change in the growth rate of GRP is calculated as the projected change in extreme heat multiplied by the coefficient of the respective hot days or heat waves variable from Figures 1 and 2 (e.g., top 3% hot days, top 5% hot days, heat waves with at least 3 consecutive days of top 3% hot days, and heat waves with at least 3 consecutive days of top 5% hot days). In Panel B, the share is computed as a ratio. The numerator (shown in Panel A) is the product of the coefficient of the respective hot days or heat waves variable from Figures 1 and 2 and the projected increase in hot days or heat waves. The denominator is the numerator plus the coefficient of each seasonal mean temperature multiplied by the projected change in seasonal mean temperatures. Regions are ordered from coolest to hottest based on their average temperature in the period of analysis (1970-2010).

Tables

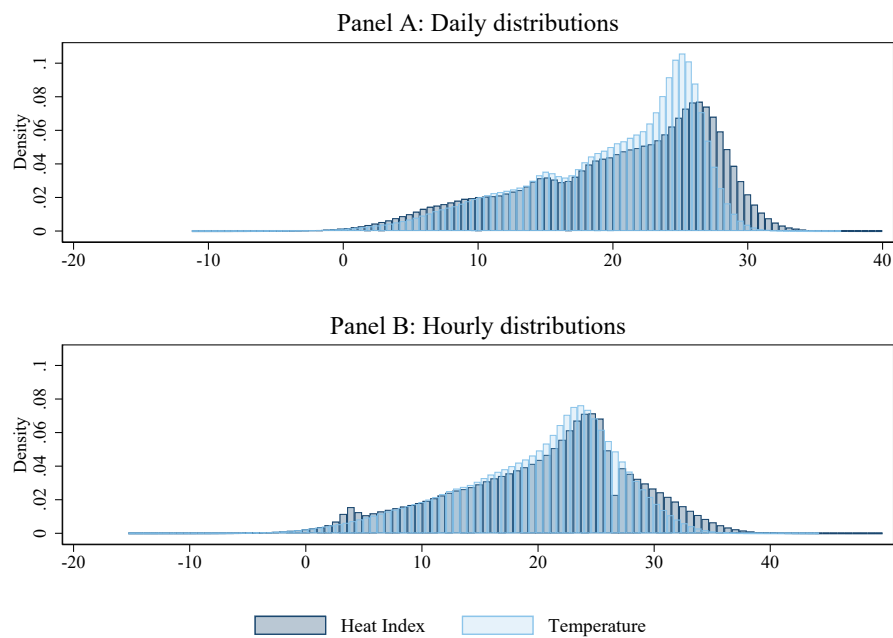
Table 1: Effects of Heat Index and Temperature on the Growth Rate of GRP

	Heat Index			Temperature		
	(1) Annual Mean	(2) Daily Mean	(3) Hourly	(4) Annual Mean	(5) Daily Mean	(6) Hourly
Annual Mean	-0.693*** (0.113)			-1.119*** (0.214)		
Bin 1		0.00370 (0.00847)	0.00108* (0.000642)		-0.00338 (0.00742)	0.000349 (0.000583)
Bin 2		0.00971* (0.00551)	0.000741* (0.000405)		-0.00140 (0.00440)	0.000315 (0.000420)
Bin 4		-0.0148*** (0.00391)	-0.00145*** (0.000306)		-0.0156*** (0.00388)	-0.00131*** (0.000323)
Bin 5		-0.0353*** (0.00675)	-0.00345*** (0.000633)		-0.0363*** (0.00718)	-0.00349*** (0.000664)
Observations	7498	7498	7498	7498	7498	7498
R^2	0.168	0.173	0.175	0.166	0.172	0.174

Notes: Columns (1) and (4) present the effect of the average annual heat index and temperature, respectively, on the growth rate of per capita GRP. The independent variables in Columns (2) and (5) correspond to the annual count of days that the daily mean heat index and the daily mean temperature fall into a given range. In Column (2), the bins are: below 7C (Bin 1), equal to 7C and up to 14C (Bin 2), equal to 21C and up to 28C (Bin 4), or above 28C (Bin 5). In Column (5), the bins are: below 9C (Bin 1), equal to 9C and up to 15C (Bin 2), equal to 21C and up to 27C (Bin 4), or above 27C (Bin 5). The independent variables in Columns (3) and (6) correspond to the annual count of hours that the heat index and temperature fall into a given range. In Column (3), the bins are: below 5C (Bin 1), equal to 5C and up to 14C (Bin 2), equal to 23C and up to 32C (Bin 4), or above 32C (Bin 5). In Column (6), the bins are: below 7C (Bin 1), equal to 7C and up to 15C (Bin 2), equal to 22C and up to 30C (Bin 4), or above 30C (Bin 5). All regressions control for mean monthly precipitation and the lagged dependent variable and include year and region and year fixed effects. Standard errors in parentheses are clustered by region. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

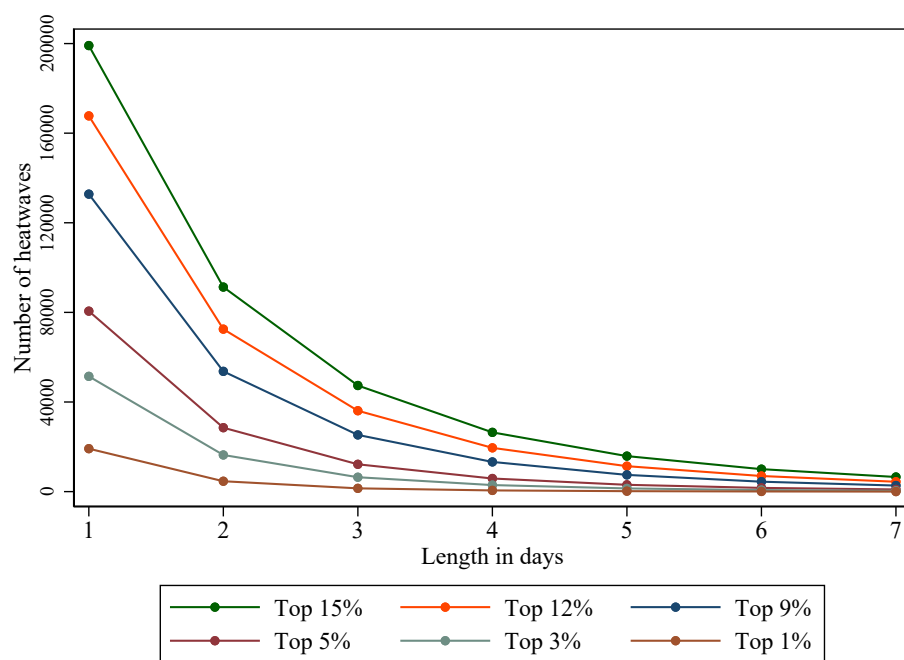
Appendix Figures

Figure A1: Distributions of Daily Mean and Hourly Temperature and Heat Index



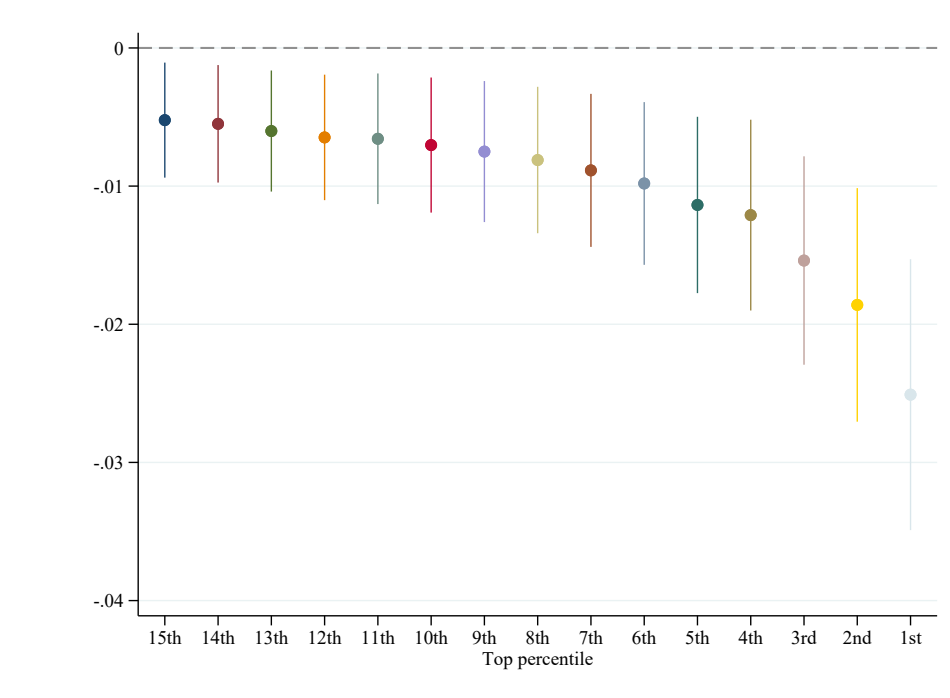
Notes: Panel A shows the distributions of the daily mean temperature and the daily mean heat index from 1970-2010. Panel B shows the distributions of the hourly temperature and the hourly heat index from 1970-2010.

Figure A2: Number of Heat Waves by Heat Index Intensity and Duration



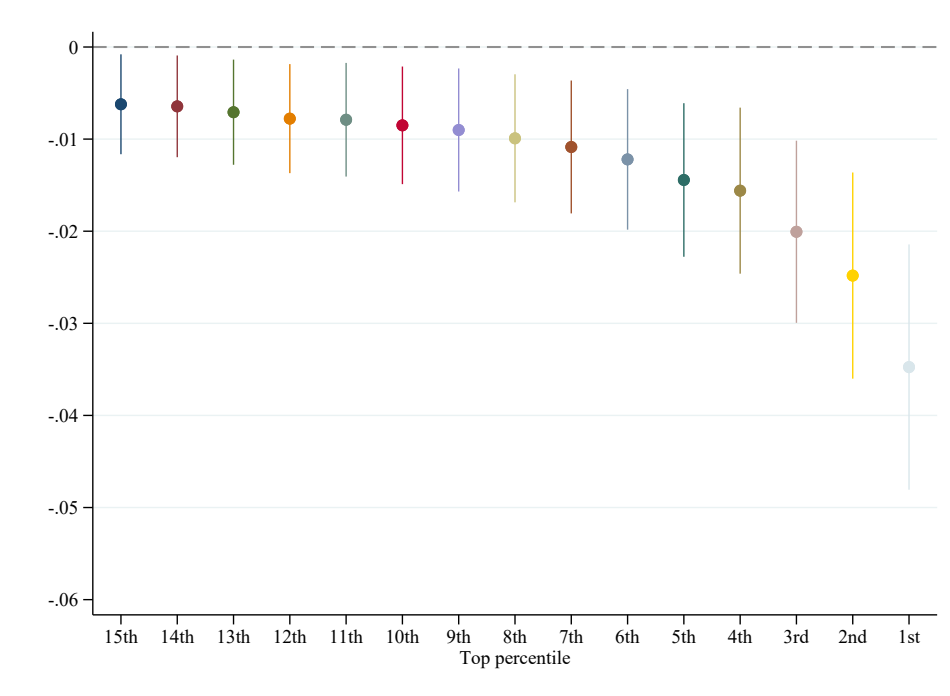
Notes: The figure shows the number of heat waves of each intensity and duration present in the data for the 272 regions from 1970 to 2010. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month.

Figure A3: Effect of Hot Days on the Growth Rate of GRP Winsorizing at the 95th and 5th Percentiles



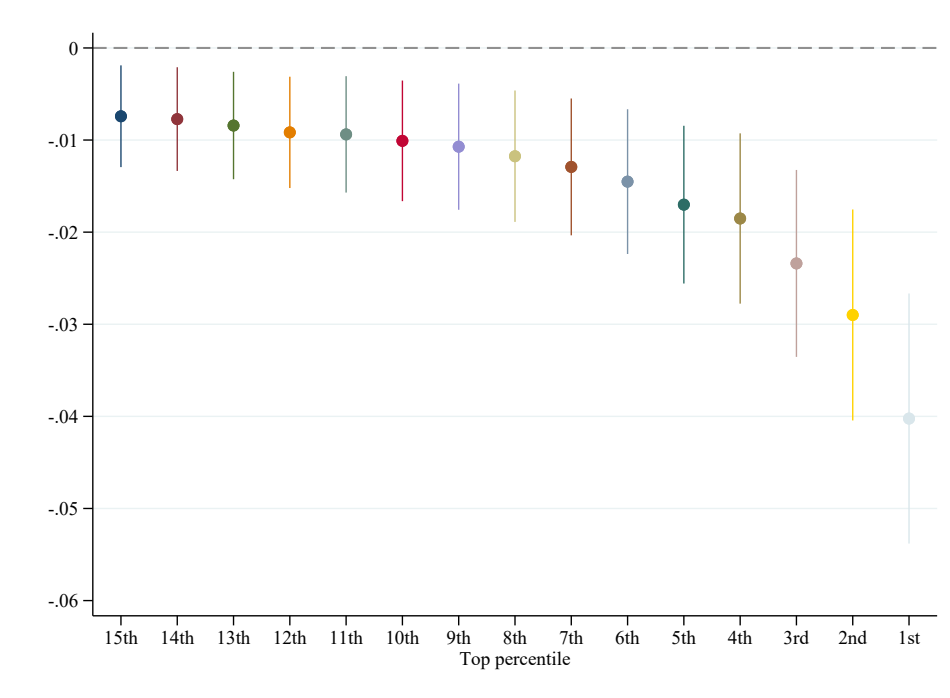
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for the real exchange rate, mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year*country fixed effects. Standard errors are clustered by region.

Figure A4: Effect of Hot Days on the Growth Rate of GRP Including Regional Trends



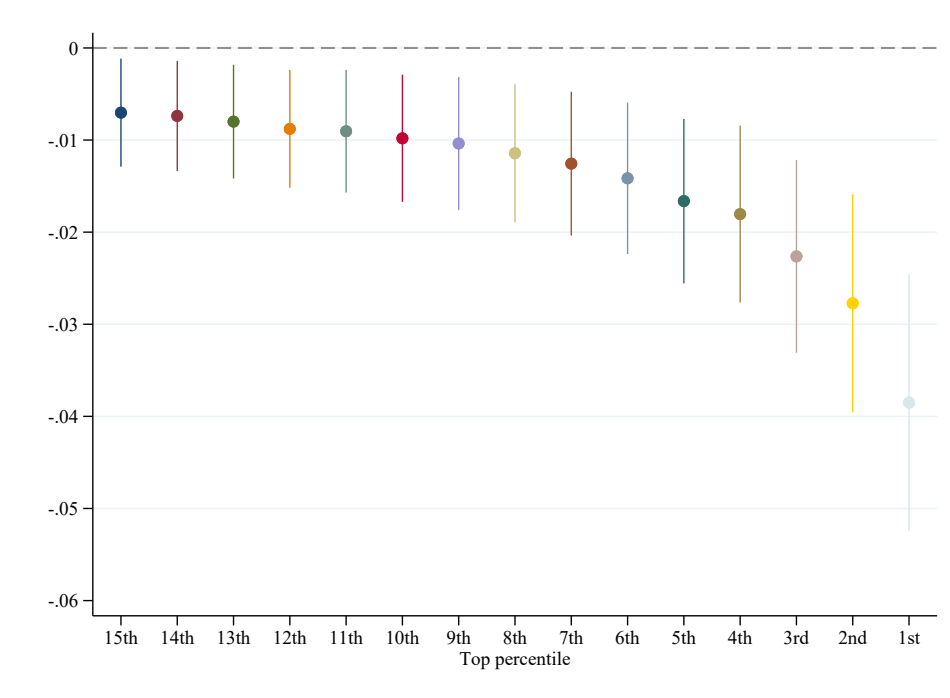
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects and linear and quadratic region trends. Standard errors are clustered by region.

Figure A5: Effect of Hot Days on the Growth Rate of GRP Controlling for Annual Temperature



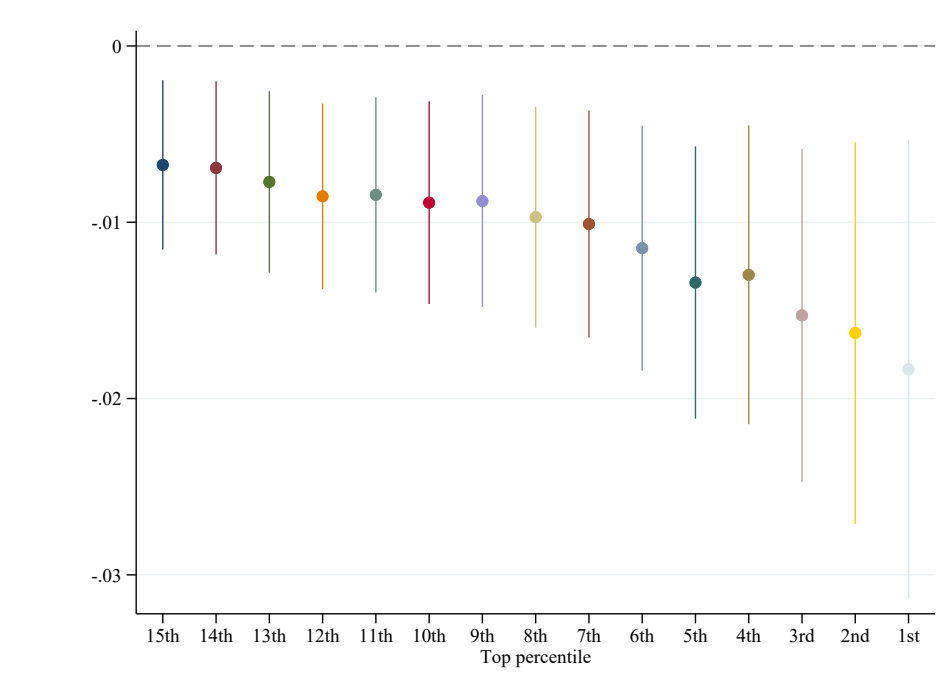
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, annual mean temperature, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by region.

Figure A6: Effect of Hot Days on the Growth Rate of GRP without Controlling for the Lag of GRP Growth Rate



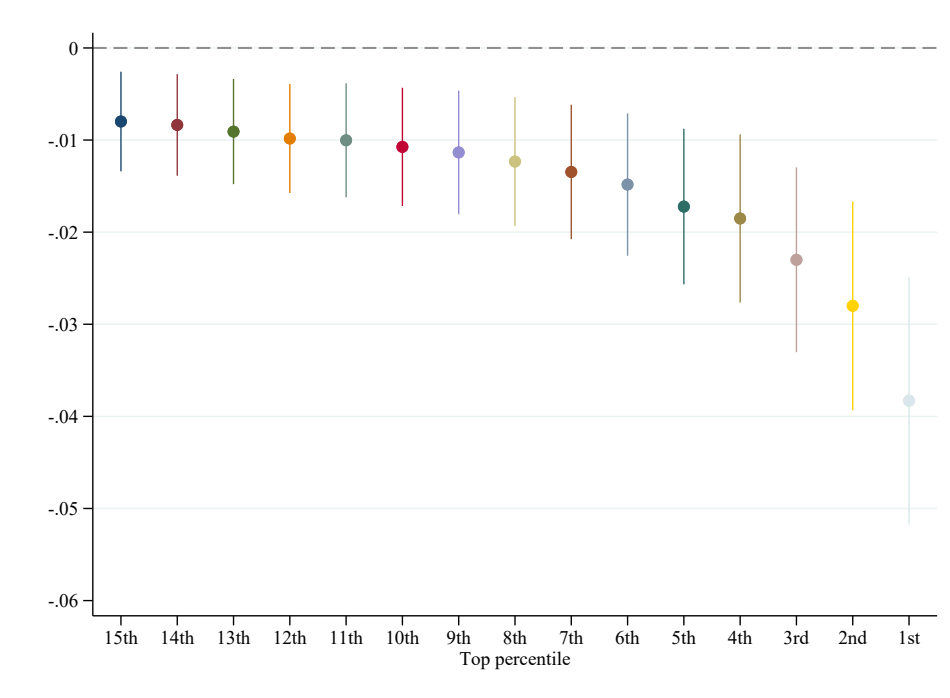
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and includes year and region fixed effects. Standard errors are clustered by region.

Figure A7: Effect of Hot Days on the Growth Rate of GRP Including Year*Country Fixed Effects



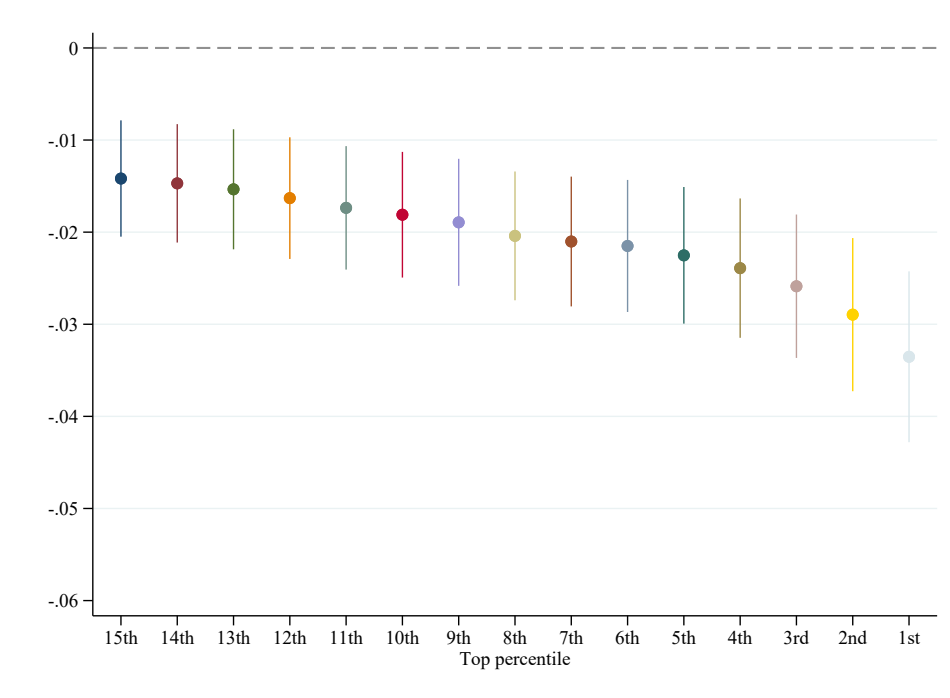
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for the mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year*country fixed effects. Standard errors are clustered by region.

Figure A8: Effect of Hot Days on the Growth Rate of GRP Controlling for the Real Exchange Rate



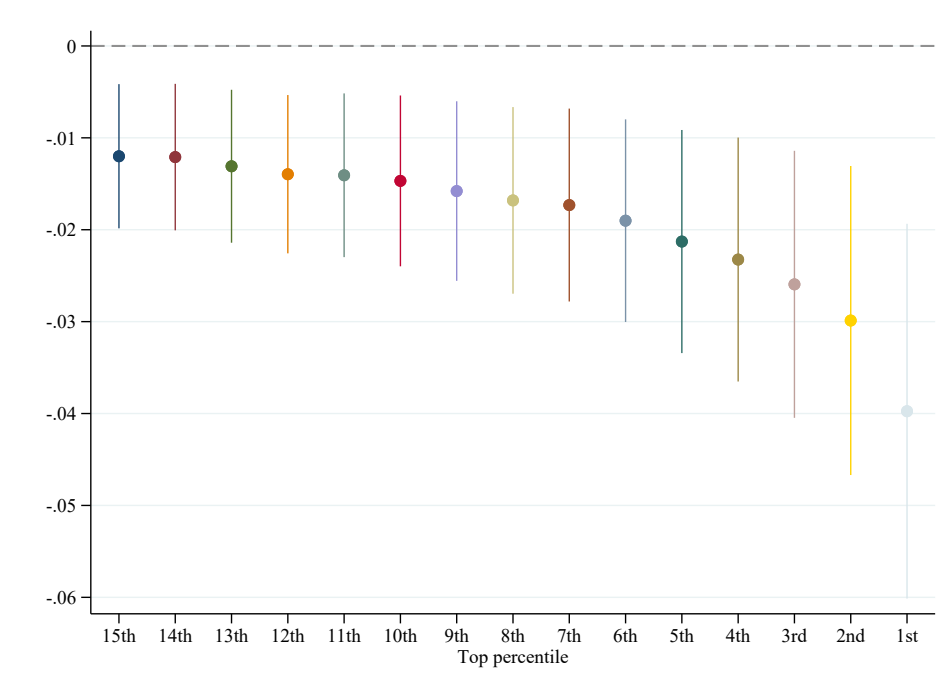
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for the real exchange rate, mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Figure A9: Effect of Hot Days Defined Using 1960-1969 Distributions on the Growth Rate of GRP



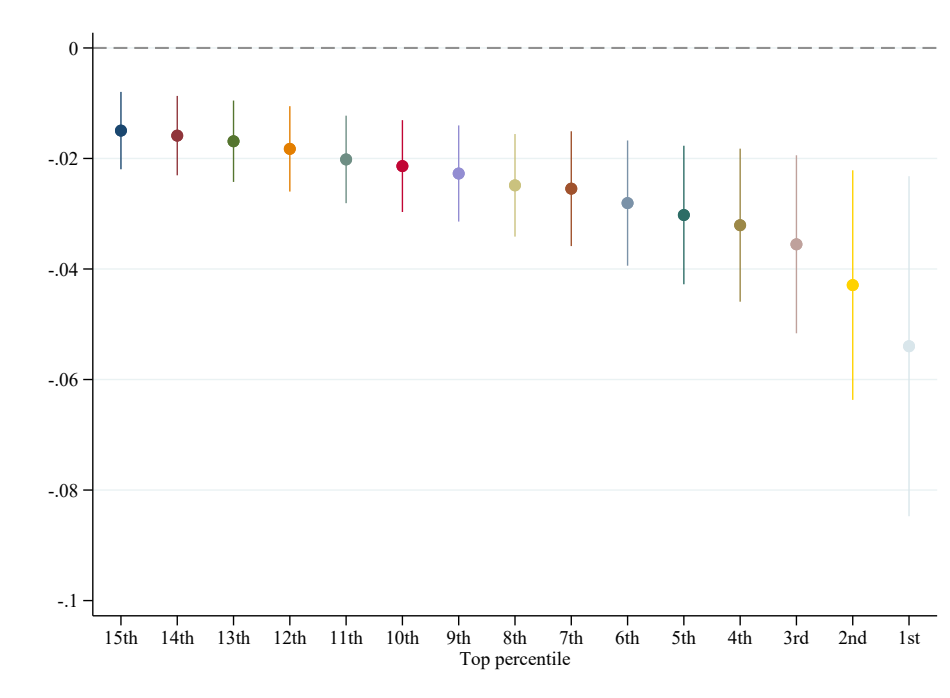
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index that is in the top percentile of the maximum daily heat indexes over the pre-analysis period (1960-1969) by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by region.

Figure A10: Effect of Hot Days in Hot Region-Months on the Growth Rate of GRP



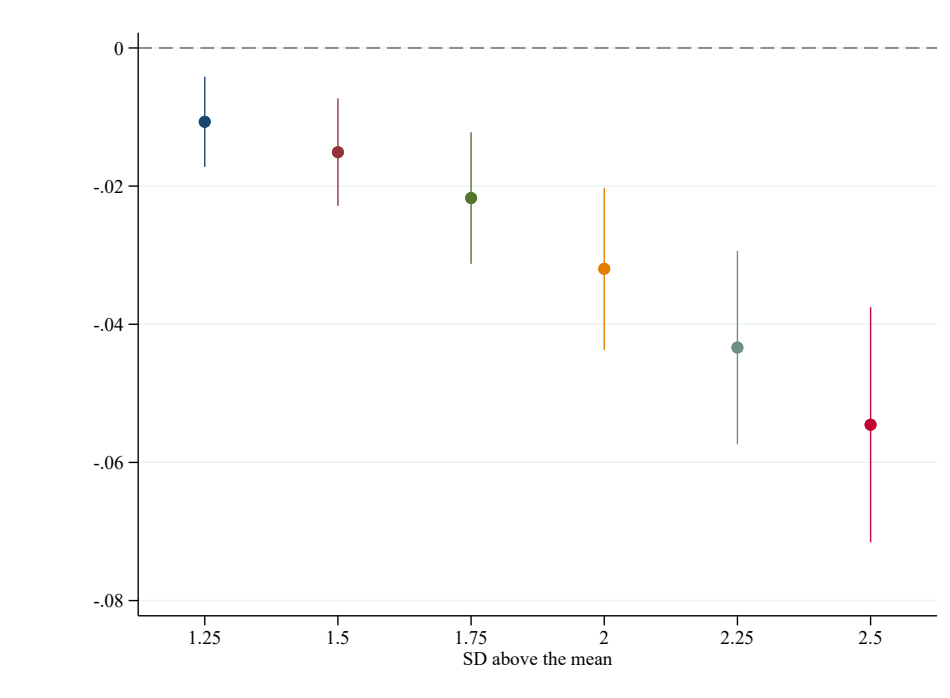
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Figure A11: Effect of Hot Days Defined by Temperature on the Growth Rate of GRP



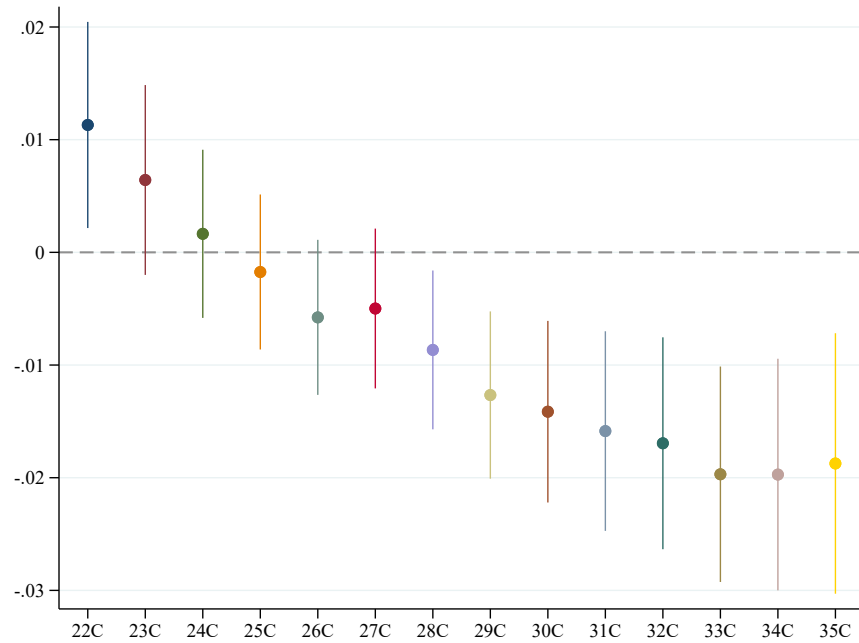
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum temperature in the top percentile of the distribution of the maximum daily temperatures over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by region.

Figure A12: Effect of Hot Days Defined by Standard Deviation on the Growth Rate of GRP



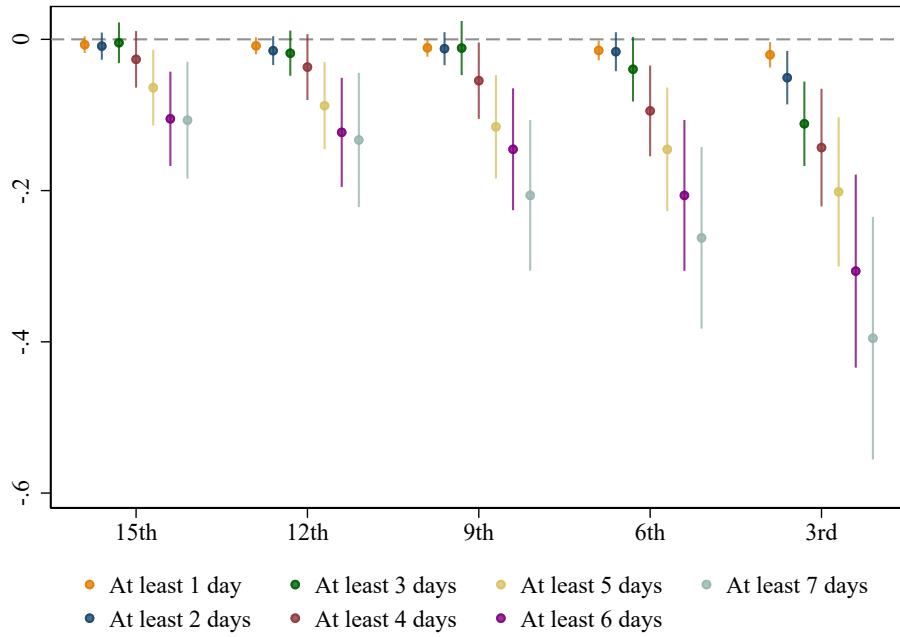
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index that is different standard deviations above the mean of the maximum daily heat indexes over the previous decade by region-month on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by region.

Figure A13: Effect of Hot Days Defined by Degrees Celsius of the Heat Index on the Growth Rate of GRP



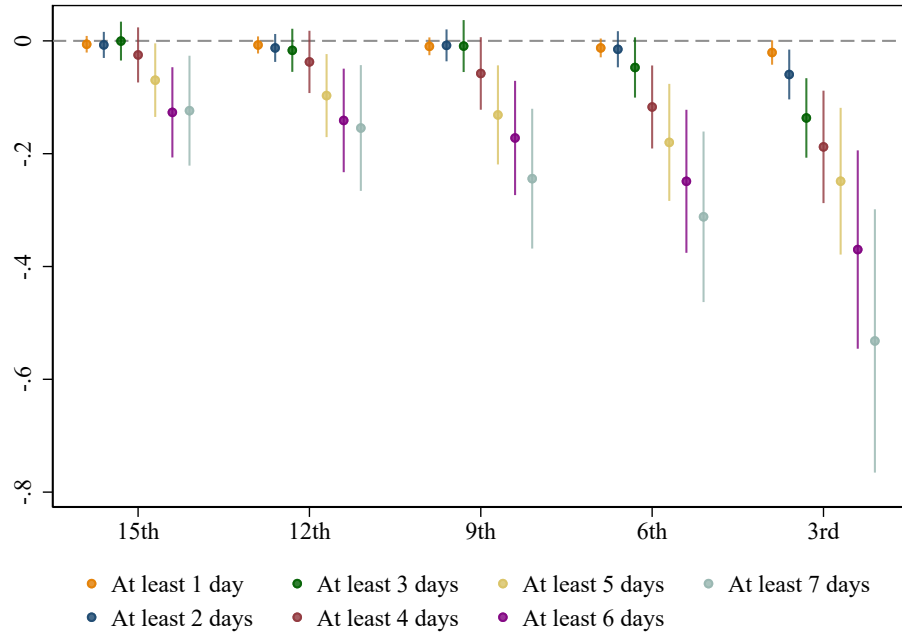
Notes: Each dot represents the coefficient from a separate regression of the annual count of days with a maximum heat index above different thresholds in °C on the growth rate of per capita GRP. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Figure A14: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration Winsorizing at the 95th and 5th Percentiles



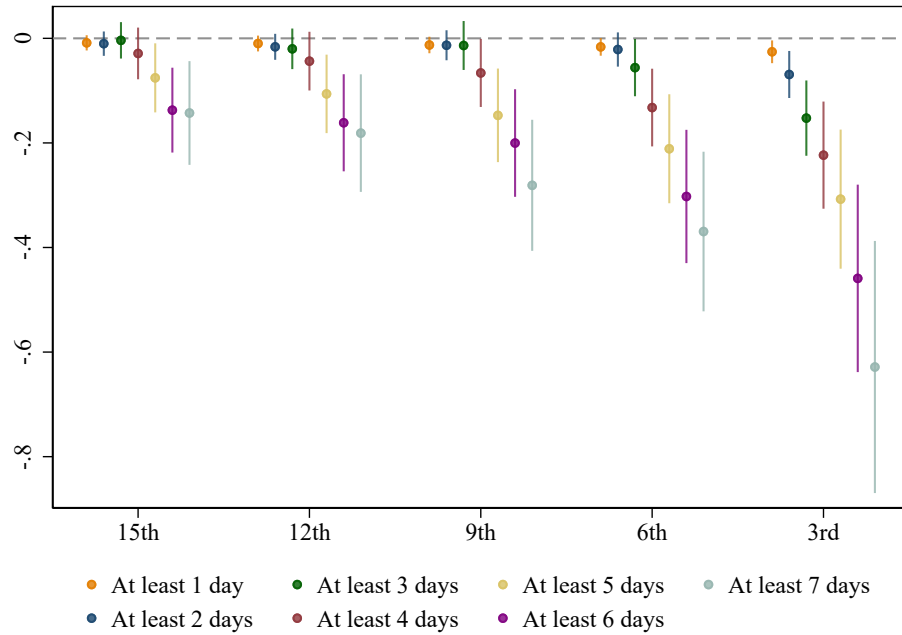
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for the real exchange rate, mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year*country fixed effects. Standard errors are clustered by region.

Figure A15: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration Controlling for Regional Trends



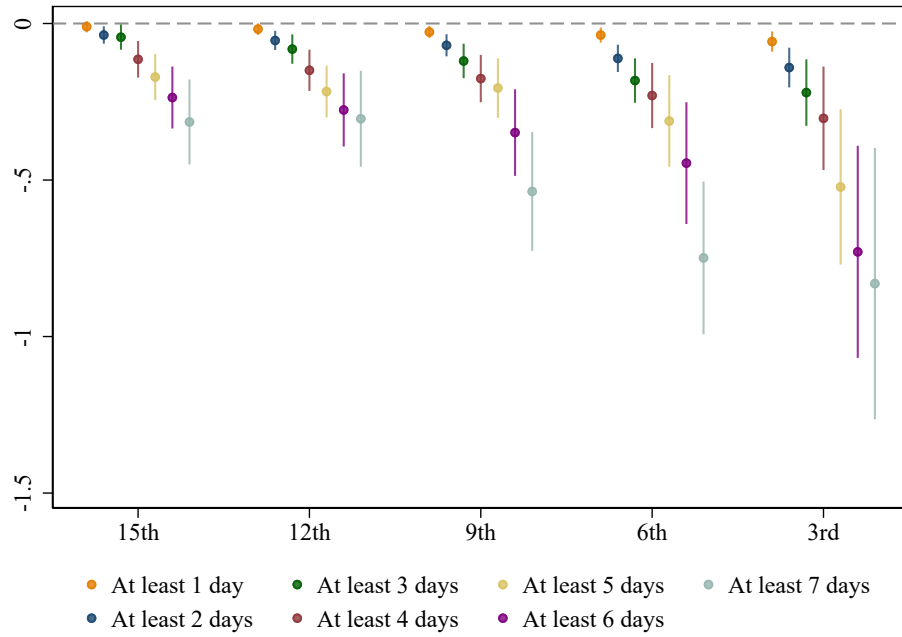
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each heat index intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects and linear and quadratic region trends. Standard errors are clustered by regions.

Figure A16: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration Controlling for Annual Temperature



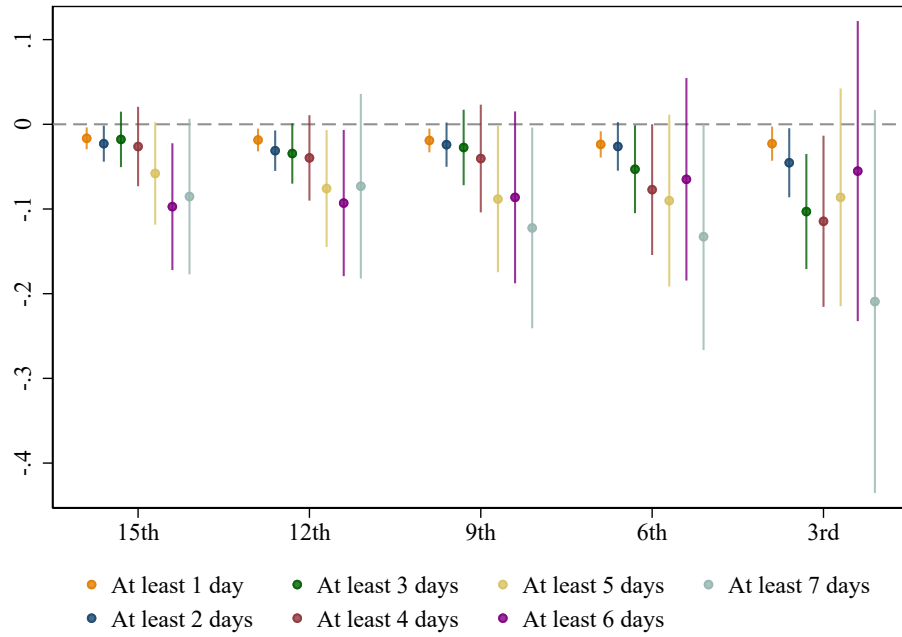
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each heat index intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean annual temperature, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by regions.

Figure A17: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration without Controlling for the Lag of the GRP Growth Rate



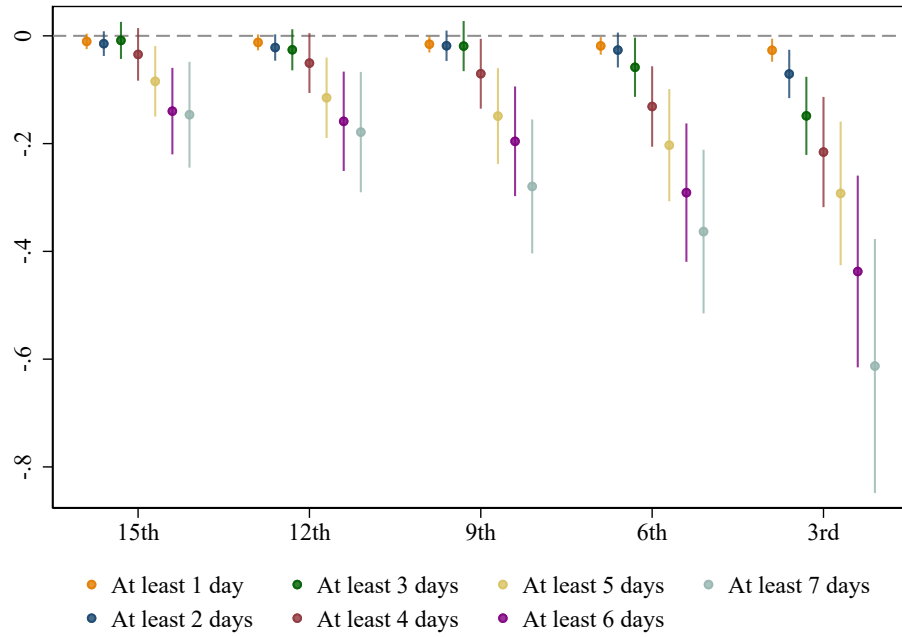
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each heat index intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation and mean seasonal temperatures and includes year and region fixed effects. Standard errors are clustered by regions.

Figure A18: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration Including Year*Country Fixed Effects



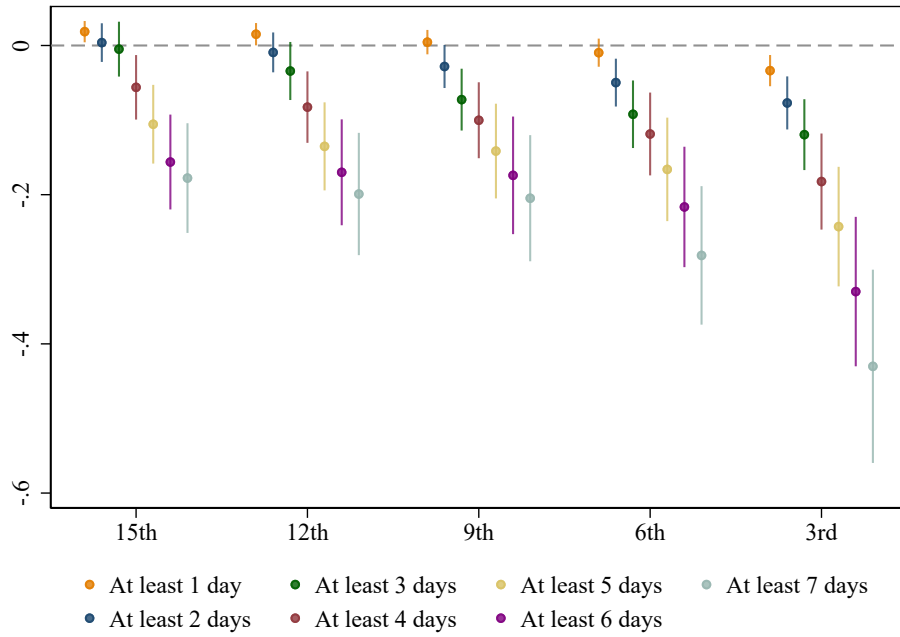
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for the mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year*country fixed effects. Standard errors are clustered by region.

Figure A19: Effect of Heat Waves on the Growth Rate of GRP by Intensity and Duration Controlling for the Real Exchange Rate



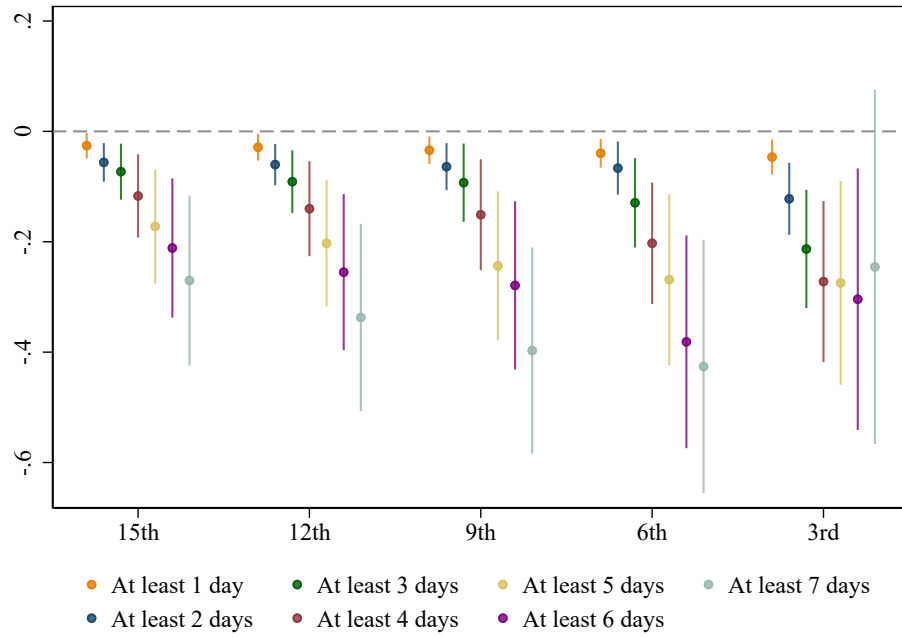
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for the real exchange rate, mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Figure A20: Effect of Heat Waves Defined Using 1960-1969 Distributions on the Growth Rate of GRP by Intensity and Duration



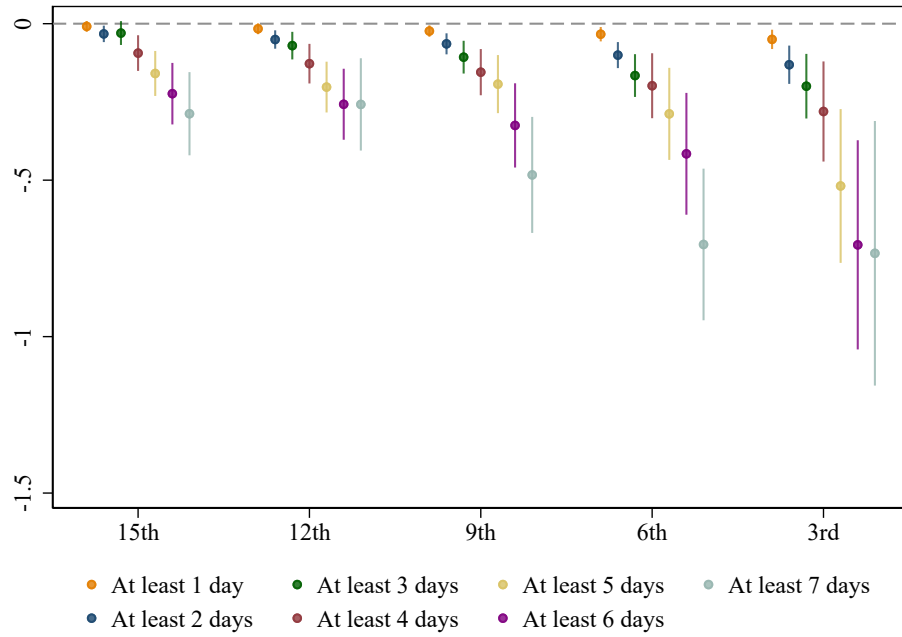
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each heat index intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the pre-analysis period (1960-1969) by region-month. 90% confidence intervals are shown. Each regression controls for monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by regions.

Figure A21: Effect of Heat Waves in Hot Region-Months on the Growth Rate of GRP by Intensity and Duration



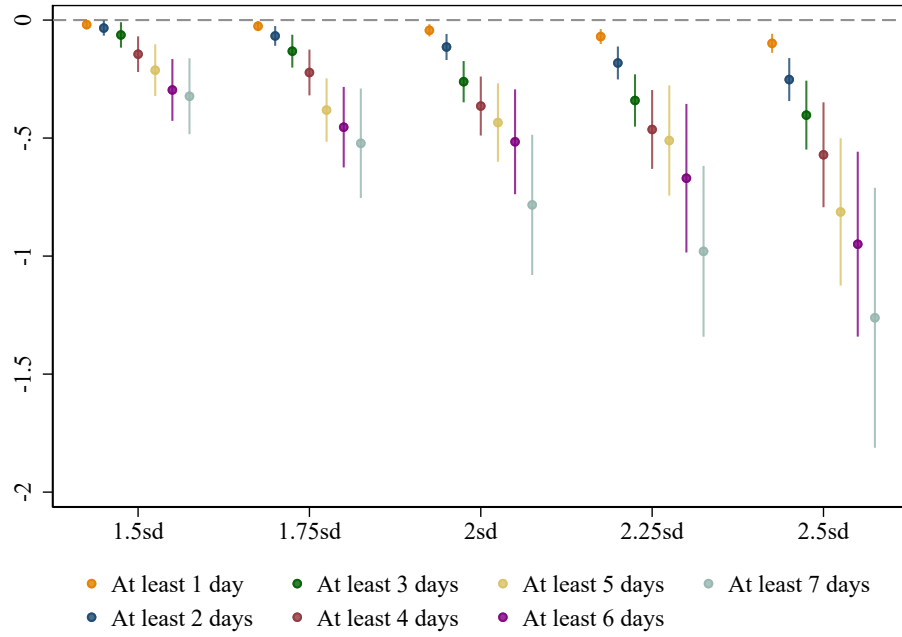
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Figure A22: Effect of Heat Waves Defined by Temperature on the Growth Rate of GRP by Intensity and Duration



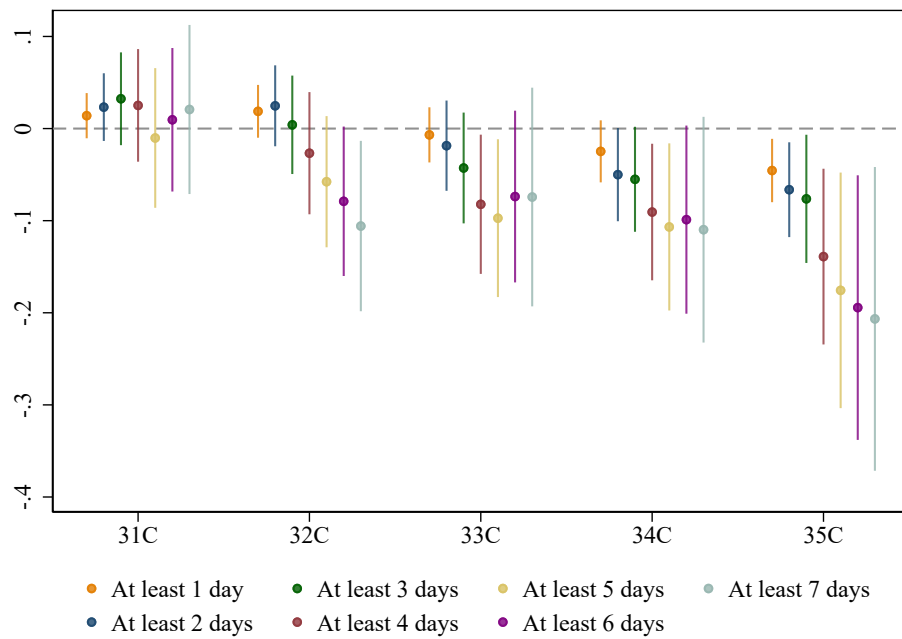
Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each temperature intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum temperature in the top percentile of the distribution of the maximum daily temperatures over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by regions.

Figure A23: Effect of Heat Waves Defined by Standard Deviation on the Growth Rate of GRP by Intensity and Duration



Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each heat index intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index that is a number of standard deviations above the mean of the distribution of the maximum daily heat indexes over the previous decade by region-month. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by regions.

Figure A24: Effect of Heat Waves Defined by Degrees Celsius of the Heat Index on the Growth Rate of GRP by Intensity and Duration



Notes: Each dot represents the coefficient from a separate regression of the annual count of heat waves of each intensity and duration on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index above different thresholds in °C. 90% confidence intervals are shown. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable, and includes year and region fixed effects. Standard errors are clustered by region.

Appendix Tables

Table A1: Description of the Sample

	Observations	Regions in the sample	Regions in the country
Argentina	840	24	24
Bolivia	270	9	9
Brazil	819	20	27
Chile	455	13	16
Colombia	973	24	32
Ecuador	286	21	24
El Salvador	154	14	14
Guatemala	242	22	22
Honduras	240	16	18
Mexico	1,312	32	32
Nicaragua	217	7	17
Panama	108	9	9
Peru	782	23	25
Uruguay	627	19	19
Venezuela	399	21	23
Total	7,724	274	302

Notes: Chile, Ecuador, Honduras, Nicaragua, and Venezuela have economic data for a subset of their regions. In addition, Brazil has economic data covering all of its regions, but 10 regions are aggregated into 3. Peru has data covering all of its 25 regions, but 4 regions are aggregated into 2. Colombia has data for all of its 32 regions, but 9 of them are aggregated into 1.

Table A2: Number of Region-Days in Each Top Percentile

Panel A								
	Top 15%	Top 14%	Top 13%	Top 12%	Top 11%	Top 10%	Top 9%	Top 8%
Argentina	1,365	1,280	1,194	1,108	1,024	926	832	745
Bolivia	597	563	529	494	460	419	378	341
Brazil	1,429	1,349	1,268	1,184	1,105	1,014	920	831
Chile	769	721	672	626	581	527	474	427
Colombia	1,514	1,424	1,336	1,248	1,162	1,060	964	871
Ecuador	1,172	1,101	1,032	958	888	808	732	659
El Salvador	1,177	1,117	1,057	995	934	866	794	722
Guatemala	1,451	1,370	1,287	1,201	1,113	1,016	915	830
Honduras	839	787	734	681	630	570	508	456
Mexico	2,263	2,139	2,011	1,883	1,758	1,611	1,462	1,327
Nicaragua	476	449	422	391	365	334	304	276
Panama	696	656	618	581	544	501	457	415
Peru	1,473	1,382	1,291	1,199	1,110	1,008	907	817
Uruguay	1,089	1,020	952	884	817	742	667	600
Venezuela	1,442	1,362	1,279	1,196	1,115	1,020	925	842
Panel B								
	Top 7%	Top 6%	Top 5%	Top 4%	Top 3%	Top 2%	Top 1%	
Argentina	660	574	489	402	311	223	133	
Bolivia	306	270	234	197	157	115	72	
Brazil	746	656	570	481	384	286	179	
Chile	380	332	286	237	186	134	81	
Colombia	777	683	590	493	394	290	183	
Ecuador	587	514	442	366	289	211	127	
El Salvador	653	581	510	430	346	253	156	
Guatemala	741	651	559	464	369	273	171	
Honduras	404	343	290	237	182	128	75	
Mexico	1,191	1,053	915	767	615	451	280	
Nicaragua	245	214	186	157	126	93	58	
Panama	374	330	287	245	204	158	105	
Peru	726	637	553	466	379	291	199	
Uruguay	533	462	395	327	257	184	114	
Venezuela	755	663	577	485	389	289	181	

Notes: Number of days in each country (summing all regions) with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month.

Table A3: Effects of Heat Index and Temperature on the Growth Rate of GRP Winsorizing at the 95th and 5th Percentiles

	Heat Index			Temperature		
	(1) Annual Mean	(2) Daily Mean	(3) Hourly	(4) Annual Mean	(5) Daily Mean	(6) Hourly
Annual Mean	-0.493*** (0.0844)			-0.801*** (0.158)		
Bin 1		0.000845 (0.00681)	0.000652 (0.000474)		-0.00135 (0.00571)	0.000163 (0.000430)
Bin 2		0.00659 (0.00425)	0.000471* (0.000273)		-0.000406 (0.00326)	0.000198 (0.000291)
Bin 4		-0.0106*** (0.00306)	-0.00110*** (0.000224)		-0.0118*** (0.00297)	-0.00102*** (0.000229)
Bin 5		-0.0253*** (0.00546)	-0.00257*** (0.000486)		-0.0275*** (0.00591)	-0.00268*** (0.000535)
Observations	7498	7498	7498	7498	7498	7498
R^2	0.212	0.217	0.219	0.211	0.216	0.218

Notes: Columns (1) and (4) present the effect of the average annual heat index and temperature, respectively, on the growth rate of per capita GRP. The independent variables in Columns (2) and (5) correspond to the annual count of days that the daily mean heat index and the daily mean temperature fall into a given range. In Column (2), the bins are: below 7C (Bin 1), equal to 7C and up to 14C (Bin 2), equal to 21C and up to 28C (Bin 4), or above 28C (Bin 5). In Column (5), the bins are: below 9C (Bin 1), equal to 9C and up to 15C (Bin 2), equal to 21C and up to 27C (Bin 4), or above 27C (Bin 5). The independent variables in Columns (3) and (6) correspond to the annual count of hours that the heat index and temperature fall into a given range. In Column (3), the bins are: below 5C (Bin 1), equal to 5C and up to 14C (Bin 2), equal to 23C and up to 32C (Bin 4), or above 32C (Bin 5). In Column (6), the bins are: below 7C (Bin 1), equal to 7C and up to 15C (Bin 2), equal to 22C and up to 30C (Bin 4), or above 30C (Bin 5). All regressions control for the real exchange rate mean monthly precipitation and the lagged dependent variable and include year*country fixed effects. Standard errors in parentheses are clustered by region. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

Table A4: Effects of Heat Index and Temperature on the Growth Rate of GRP without Controlling for the Lag of the GRP Growth Rate

	Heat Index			Temperature		
	(1) Annual Mean	(2) Daily Mean	(3) Hourly	(4) Annual Mean	(5) Daily Mean	(6) Hourly
Annual Mean	-0.721*** (0.117)			-1.169*** (0.220)		
Bin 1		-0.000160 (0.00901)	0.000614 (0.000671)		-0.00660 (0.00779)	0.000161 (0.000722)
Bin 2		0.0106* (0.00588)	0.000753* (0.000399)		-0.000248 (0.00437)	0.000496 (0.000555)
Bin 4		-0.0156*** (0.00393)	-0.00151*** (0.000305)		-0.0164*** (0.00389)	-0.00139*** (0.000512)
Bin 5		-0.0374*** (0.00687)	-0.00364*** (0.000660)		-0.0385*** (0.00737)	-0.00353*** (0.000751)
Observations	7724	7724	7724	7724	7724	7724
R^2	0.155	0.162	0.165	0.153	0.161	0.133

Notes: Columns (1) and (4) present the effect of the average annual heat index and temperature, respectively, on the growth rate of per capita GRP. The independent variables in Columns (2) and (5) correspond to the annual count of days that the daily mean heat index and the daily mean temperature fall into a given range. In Column (2), the bins are: below 7C (Bin 1), equal to 7C and up to 14C (Bin 2), equal to 21C and up to 28C (Bin 4), or above 28C (Bin 5). In Column (5), the bins are: below 9C (Bin 1), equal to 9C and up to 15C (Bin 2), equal to 21C and up to 27C (Bin 4), or above 27C (Bin 5). The independent variables in Columns (3) and (6) correspond to the annual count of hours that the heat index and the temperature fall into a given range. In Column (3), the bins are: below 5C (Bin 1), equal to 5C and up to 14C (Bin 2), equal to 23C and up to 32C (Bin 4), or above 32C (Bin 5). In Column (6), the bins are: below 7C (Bin 1), equal to 7C and up to 15C (Bin 2), equal to 22C and up to 30C (Bin 4), or above 30C (Bin 5). All regressions control for mean monthly precipitation and include year and region fixed effects. Standard errors in parentheses are clustered by region. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

Table A5: Effects of Heat Index and Temperature on the Growth Rate of GRP Including Year*Country Fixed Effects

	Heat Index			Temperature		
	(1) Annual Mean	(2) Daily Mean	(3) Hourly	(4) Annual Mean	(5) Daily Mean	(6) Hourly
Annual Mean	-0.00777 (0.00772)			-0.0182 (0.0161)		
Bin 1		0.00140 (0.00116)	0.0000736 (0.0000749)		0.00152 (0.000998)	0.0000844 (0.0000641)
Bin 2		0.00154 (0.00116)	0.0000825 (0.0000673)		0.00110 (0.00118)	0.0000757 (0.0000707)
Bin 4		-0.000118 (0.000762)	0.0000223 (0.0000534)		-0.000164 (0.000729)	0.0000186 (0.0000457)
Bin 5		-0.000156 (0.000998)	-0.00000832 (0.000126)		-0.000429 (0.00128)	0.0000117 (0.000139)
Observations	7498	7498	7498	7498	7498	7498
R^2	0.379	0.381	0.381	0.379	0.381	0.381

Notes: Columns (1) and (4) present the effect of the average annual heat index and temperature, respectively, on the growth rate of per capita GRP. The independent variables in Columns (2) and (5) correspond to the annual count of days that the daily mean heat index and the daily mean temperature fall into a given range. In Column (2), the bins are: below 7C (Bin 1), equal to 7C and up to 14C (Bin 2), equal to 21C and up to 28C (Bin 4), or above 28C (Bin 5). In Column (5), the bins are: below 9C (Bin 1), equal to 9C and up to 15C (Bin 2), equal to 21C and up to 27C (Bin 4), or above 27C (Bin 5). The independent variables in Columns (3) and (6) correspond to the annual count of hours that the heat index and temperature fall into a given range. In Column (3), the bins are: below 5C (Bin 1), equal to 5C and up to 14C (Bin 2), equal to 23C and up to 32C (Bin 4), or above 32C (Bin 5). In Column (6), the bins are: below 7C (Bin 1), equal to 7C and up to 15C (Bin 2), equal to 22C and up to 30C (Bin 4), or above 30C (Bin 5). All regressions control for the mean monthly precipitation and the lagged dependent variable and include year*country fixed effects. Standard errors in parentheses are clustered by region. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

Table A6: Effects of Heat Index and Temperature on the Growth Rate of GRP Controlling for the Real Exchange Rate

	Heat Index			Temperature		
	(1) Annual Mean	(2) Daily Mean	(3) Hourly	(4) Annual Mean	(5) Daily Mean	(6) Hourly
Annual Mean	-0.702*** (0.115)			-1.110*** (0.219)		
Bin 1		0.00344 (0.00844)	0.00113* (0.000642)		-0.00365 (0.00728)	0.000372 (0.000583)
Bin 2		0.00861 (0.00549)	0.000696* (0.000398)		-0.00186 (0.00425)	0.000273 (0.000415)
Bin 4		-0.0158*** (0.00399)	-0.00142*** (0.000310)		-0.0168*** (0.00398)	-0.00129*** (0.000325)
Bin 5		-0.0368*** (0.00679)	-0.00353*** (0.000637)		-0.0376*** (0.00725)	-0.00347*** (0.000670)
Observations	7338	7338	7338	7338	7338	7338
R^2	0.174	0.180	0.182	0.172	0.179	0.180

Notes: Columns (1) and (4) present the effect of the average annual heat index and temperature, respectively, on the growth rate of per capita GRP. The independent variables in Columns (2) and (5) correspond to the annual count of days that the daily mean heat index and the daily mean temperature fall into a given range. In Column (2), the bins are: below 7C (Bin 1), equal to 7C and up to 14C (Bin 2), equal to 21C and up to 28C (Bin 4), or above 28C (Bin 5). In Column (5), the bins are: below 9C (Bin 1), equal to 9C and up to 15C (Bin 2), equal to 21C and up to 27C (Bin 4), or above 27C (Bin 5). The independent variables in Columns (3) and (6) correspond to the annual count of hours that the heat index and temperature fall into a given range. In Column (3), the bins are: below 5C (Bin 1), equal to 5C and up to 14C (Bin 2), equal to 23C and up to 32C (Bin 4), or above 32C (Bin 5). In Column (6), the bins are: below 7C (Bin 1), equal to 7C and up to 15C (Bin 2), equal to 22C and up to 30C (Bin 4), or above 30C (Bin 5). All regressions control for the real exchange rate, mean monthly precipitation, and the lagged dependent variable and include year and region and year fixed effects. Standard errors in parentheses are clustered by region. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$.

Table A7: Effect of Hot Days on the Growth Rate of GRP

Panel A : Growth rate of GRP							
	15%	14%	13%	12%	11%	10%	9%
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Hot days	-0.00733** (0.00333)	-0.00762** (0.00340)	-0.00830** (0.00352)	-0.00901** (0.00364)	-0.00920** (0.00381)	-0.00987** (0.00394)	-0.0104** (0.00412)
Observations	7498	7498	7498	7498	7498	7498	7498
R^2	0.174	0.174	0.175	0.175	0.175	0.175	0.175
Panel B : Growth rate of GRP							
	7%	6%	5%	4%	3%	2%	1%
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Hot days	-0.0125*** (0.00447)	-0.0140*** (0.00473)	-0.0163*** (0.00516)	-0.0177*** (0.00557)	-0.0223*** (0.00612)	-0.0274*** (0.00690)	-0.0379*** (0.00816)
Observations	7498	7498	7498	7498	7498	7498	7498
R^2	0.175	0.175	0.175	0.175	0.176	0.176	0.177

Notes: Each column represents a separate regression of the annual count of days with a maximum heat index in the top percentile of the distribution of maximum daily heat indexes over the previous decade by region-year on the growth rate of per capita GRP. Each regressions controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by region.

Table A8: Effects of Heat Waves on the Growth Rate of GRP by Intensity and Duration

	15%	12%	9%	6%	3%
Panel A: Growth rate of GRP					
Single day	-0.009 (0.009)	-0.011 (0.009)	-0.013 (0.010)	-0.017* (0.010)	-0.026* (0.013)
Observations	7498	7498	7498	7498	7498
R^2	0.174	0.174	0.174	0.174	0.174
Panel B: Growth rate of GRP					
2 consecutive days	-0.012 (0.014)	-0.018 (0.015)	-0.014 (0.017)	-0.022 (0.020)	-0.067** (0.027)
Observations	7498	7498	7498	7498	7498
R^2	0.174	0.174	0.174	0.174	0.174
Panel C: Growth rate of GRP					
3 consecutive days	-0.006 (0.021)	-0.022 (0.023)	-0.015 (0.028)	-0.055* (0.033)	-0.146*** (0.044)
Observations	7498	7498	7498	7498	7498
R^2	0.173	0.174	0.173	0.174	0.175
Panel D: Growth rate of GRP					
4 consecutive days	-0.029 (0.030)	-0.043 (0.034)	-0.064 (0.039)	-0.127*** (0.045)	-0.208*** (0.062)
Observations	7498	7498	7498	7498	7498
R^2	0.174	0.174	0.174	0.175	0.175
Panel E: Growth rate of GRP					
5 consecutive days	-0.075* (0.040)	-0.104** (0.045)	-0.141*** (0.054)	-0.197*** (0.063)	-0.279*** (0.081)
Observations	7498	7498	7498	7498	7498
R^2	0.174	0.174	0.175	0.175	0.175
Panel F: Growth rate of GRP					
6 consecutive days	-0.133*** (0.049)	-0.152*** (0.056)	-0.187*** (0.062)	-0.278*** (0.078)	-0.416*** (0.108)
Observations	7498	7498	7498	7498	7498
R^2	0.175	0.175	0.175	0.175	0.175
Panel G: Growth rate of GRP					
7 consecutive days	-0.135** (0.060)	-0.168** (0.068)	-0.264*** (0.076)	-0.343*** (0.093)	-0.579*** (0.144)
Observations	7498	7498	7498	7498	7498
R^2	0.174	0.174	0.175	0.175	0.176

Notes: Each column represents a separate regression of the annual count of heat waves of each intensity (specified in columns) and duration (specified in rows) on the growth rate of per capita GRP. A heat wave is defined as consecutive days with a maximum heat index in the top percentile of the distribution of the maximum daily heat indexes over the previous decade by region-month. Each regression controls for mean monthly precipitation, mean seasonal temperatures, and the lagged dependent variable and includes year and region fixed effects. Standard errors are clustered by region.

Table A9: Projected Impact of Additional Hot Days and Heat Waves (Defined by Heat Index) on the Growth of GRP at Mid-Century

Country	Region	Effect of extreme heat				Share			
		Top 3% hot days	Top 5% hot days	Top 3% hw	Top 5% hw	Top 3% hot days	Top 5% hot days	Top 3% hw	Top 5% hw
Argentina	Santa Cruz	-0.708	-0.816	-0.647	-0.729	0.446	0.486	0.296	0.351
Chile	Región Metropolitana de Santiago	-0.596	-0.674	-0.459	-0.567	0.343	0.376	0.212	0.262
Chile	Los Lagos	-0.598	-0.693	-0.438	-0.443	0.397	0.436	0.260	0.260
Peru	LimaCallao	-3.364	-3.170	-1.546	-1.260	0.347	0.417	0.146	0.182
Chile	Tarapacá	-3.145	-3.413	-2.086	-1.732	0.584	0.637	0.386	0.396
Argentina	Ciudad de Buenos Aires	-0.491	-0.564	-0.570	-0.510	0.369	0.404	0.296	0.301
Venezuela	Mérida	-2.812	-3.231	-1.076	-1.029	0.564	0.621	0.226	0.257
Colombia	Cundinamarca	-3.413	-3.890	-1.068	-1.244	0.588	0.650	0.178	0.240
Argentina	Santa Fe	-0.883	-0.965	-0.617	-0.593	0.471	0.497	0.282	0.286
Brazil	São Paulo	-1.962	-2.114	-2.110	-1.788	0.582	0.608	0.483	0.474
Venezuela	Distrito Capital	-3.449	-3.527	-1.076	-1.312	0.682	0.692	0.286	0.357
Ecuador	Guayas	-2.051	-2.355	-0.834	-0.874	0.377	0.414	0.135	0.186
Bolivia	Santa Cruz	-1.626	-1.756	-1.402	-1.547	0.544	0.575	0.372	0.457
Brazil	Ceará	-5.128	-5.276	-1.602	-1.393	0.681	0.726	0.289	0.310

Notes: Columns (1)-(4) present the projected change in the growth rate of GRP due to changes in extreme heat by mid-century. Columns (5)-(8) present the share of the total impact of temperature changes by mid-century on the growth rate of GRP that is due to changes in extreme heat. Projections for regional changes in hot days and heat waves by 2046-2055 under the RCP 4.5 scenario are from Feron et al. (2019) and projections for changes in seasonal mean temperatures by 2041-2060 under the SSP2-4.5 scenario are from Gutiérrez et al. (2021). In columns (1)-(4), the change in the growth rate of GRP is calculated as the projected change in extreme heat multiplied by the coefficient of the respective hot days or heat waves variable from Figures 1 and 2 (e.g., top 3% hot days, top 5% hot days, heat waves with at least 3 consecutive days of top 3% hot days, and heat waves with at least 3 consecutive days of top 5% hot days). In columns (5)-(8), the share is computed as a ratio. The numerator (shown in Panel A) is the product of the coefficient of the respective hot days or heat waves variable from Figures 1 and 2 and the projected increase in hot days or heat waves. The denominator is the numerator plus the coefficient of each seasonal mean temperature multiplied by the projected change in seasonal mean temperatures. Regions are ordered from coolest to hottest based on their average temperature in the period of analysis (1970-2010).

Data Appendix

The economic data contain the following departures from the region (highest sub-national) level.

- Brazil: Ten regions (states and federal district) are aggregated into three areas with data reported for three aggregates.
 - Amazonas, Mato Grosso, Mato Grosso do Sul, Rondônia, and Roraima
 - Goiás, Distrito Federal, and Tocantins
 - Pará and Amapá
- Peru: Four regions are aggregated into two areas with economic data reported for two aggregate areas.
 - Lima and Callao
 - Loreto and Ucayali
- Colombia: Nine regions are aggregated into one area with economic data reported for the aggregate area.
 - Arauca, Casanare, Putumayo, San Andrés and Providencia, Amazonas, Guainía, Guaviare, Vaupés, and Vichada.

In addition, the Database of Global Administrative Areas provides geospatial data for Nicaragua at a level of aggregation below the highest sub-national level (i.e. level 2). Therefore, the geospatial data must be aggregated to the highest sub-national administrative level before aggregating the weather data to the region level using area weighted averages. Specifically, the following level 2 areas are aggregated into seven regions:

- Atlántico Norte & Sur
- Pacífico Central : Managua, Masaya, Granada and Corazo
- Pacífico Sur: Rivas
- Pacífico Norte: León and Chinandega
- Interior Central: Boaco and Matagalpa
- Interior Norte: Nueva Segovia, Madriz, Estelí and Jinotega
- Interior Sur: Chontales