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Rising Temperature, Nuanced Effects: Evidence from Seasonal and Sectoral Data

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Rising Temperature, Nuanced Effects: Evidence from Seasonal and Sectoral Data

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ABSTRACT: Using quarterly temperature and sectoral value-added data for a large sample of advanced economies (AEs) and emerging markets and developing economies (EMDEs), this paper uncovers nuanced effects of temperature on economic activity. For EMDEs, hotter spring and summer temperatures reduce growth in real value-added of manufacturing, and most significantly, of agriculture, while a warmer winter boosts it. For advanced countries (AEs), a hotter spring hurts growth in real value-added of all considered sectors: services, manufacturing and agriculture. For both country groups, the negative effect of a hotter spring is larger and more persistent than the positive effect of a warmer winter. Furthermore, the adverse impacts of hotter temperatures in advanced economies have accentuated in recent decades. This result suggests increased vulnerability to rising temperatures.

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WORKING PAPERS

Rising Temperature, Heterogeneous Effects: Evidence from Seasonal and Sectoral Data

Prepared by Ha Minh Nguyen and Samuel Pienknagura[1]

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I. Introduction

Climate change is an enormous challenge for humankind. The global average temperature is already about 1.1 degree Celsius higher than the pre-industrial level and they are expected to keep rising in coming years (International Panel on Climate Change, 2021). Understanding the impact of rising temperature, the most basic manifestation of climate change, on economic activity is fundamental to adaptation and mitigation efforts.

The economic literature has generally found that higher temperature hurts economic activity, more so in hotter and poorer countries. Early literature examines the relationship between average temperature and aggregate economic variables (e.g., Sachs and Warner, 1997; Gallup, Sachs, and Mellinger, 1999). It finds that hotter countries tend to be poorer. However, this relationship might be driven by omitted variables such as country institutions. Recent literature uses fluctuations in temperature within a country or a region to control for slow-moving characteristics (see for example, Dell et al., 2012; Cashin et al., 2017; Colacito et al., 2019; Letta and Tol, 2019; Acevedo et al., 2020; Kahn et al., 2021).[1] It finds that higher temperature reduces the economic growth of poor countries (Dell et al., 2012; Acevedo et al., 2020) and the US (Colacito et al., 2019). The negative effects run through reduced total factor productivity growth (Letta and Tol, 2019), reduced investment and labor productivity (Acevedo et al., 2020; Kalkuhl and Wenz, 2020) and reduced sectoral productivity (Lepore and Fernando, 2023). Burke et al. (2015) document the non-linear effect of temperature: economic growth rises with average annual temperature until around 13 degrees Celsius and drops after that. Acevedo et al (2020) also find non-linearity between temperature and activity.

The literature typically focuses on country-level and annual-average temperature and economic outcomes. (e.g., see Deschênes and Greenstone, 2007; Dell et al., 2012; Burke et al., 2015; Acevedo et al., 2020; Kalkuhl and Wenz, 2020; Berg et al., 2023; Newell et al.,2021)[2]. However, since temperature can vary greatly within a year, from freezing winters to scorching summers, this paper argues that seasonal temperature is a better approximation of weather than annual temperature. For example, highest daily temperature in Washington D.C. (United States) in 2021 ranges from 6 degrees Celsius in the winter to the 35 degrees Celsius in the summer (Figure 1). The average annual temperature for Washington D.C. is about 20 degrees Celsius. If we use this annual average of 20 degrees Celsius in our analyses, we might be mistaken that Washington D.C.'s weather is more moderate while in fact, it has a cold winter and a hot summer. Seasonal temperature (as shown in Figure 1) is argued a better approximation of temperature than annual-average temperature. More importantly, the economic structures of different seasons could be very different. More indoor activity can be planned during the winter and more outdoor activity (such as agriculture, tourism, and construction) can be planned during the spring and summer. Therefore, examining the effects of seasonal temperature on seasonal economic activity could offer new insights to complement the existing analyses using annual average temperature and annual-average economic outcomes.

This paper examines the effects of seasonal temperature on growth in quarterly value-added of agriculture, manufacturing and services for advanced economies (AEs) and emerging markets and developing economies (EMDEs). We uncover several new and nuanced impacts of temperature. The impact of rising temperature on economic activity depends on the season and sector. For emerging markets and developing countries (EMDEs), a hotter spring reduces growth in real value-added of manufacturing, and most significantly, of

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[1] Also see recent surveys by Dell et al. (2014), Auffhammer (2018), and Chang et al. (2023)

[2] Akyapi et al. (2022) identify among a large number of annual climate indicators the best to cause economic damage.

agriculture. A 1-Celsius degree hotter spring reduces year-on-year (*yoy*) growth in value-added of agriculture by about 0.8 percentage points in the same spring and by more than 1 percentage point in the following summer and fall. A hotter summer also reduces growth in agricultural value-added persistently while a hotter fall does not have a significant effect. However, a warmer winter *boosts* growth in agricultural value-added, not only in the winter but also in the following spring and summer. The findings suggest a nuanced effects of rising temperature, namely reducing growth in some seasons and boosting growth in some others. For advanced countries (AEs), a hotter spring hurts growth in real value-added of all considered sectors: services, manufacturing, and agriculture. A warmer winter *boosts* agriculture (persistently), but not manufacturing and services. Since agriculture is small in AEs, a warmer winter has a negligible impact on the aggregate economy.

Overall, for both country groups, the negative effect on the economy of a hotter spring is larger and more persistent than the positive effect of a warmer winter. For EMDEs, the more negative spring effect has to do more with agriculture and manufacturing while for AEs, it has to do with agriculture, manufacturing and services[3]. At peak, the magnitude of the negative spring aggregate effect is quite similar for EMDEs and AEs. Among sectors, agriculture is most affected by temperature. This finding is probably not so surprising because agriculture is more exposed to outside conditions. Nevertheless, this is important to document because agriculture still contributes a significant share of economic activity in EMDEs.

To summarize, a more granular approach using seasonal temperature can provide more nuanced and precise estimates of the impacts of temperature. In addition, by showing the impact by sector, it provides additional insights into the mechanisms of impacts. In turn, understanding more the mechanisms of impacts on different sectors allows governments in both AEs and EMDEs to design appropriate adaptation efforts that fit their countries' specificity.

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[3] Unlike EMDEs, in AEs, the gardening and landscaping industry is popular during the spring season. As the weather becomes more favorable for plant growth, many households seek professional assistance for planting flowers, maintaining lawns and other yard work. A hotter spring may dampen growth of this industry. Other services such as outdoor recreation (for example, bike and boat rentals, outdoor hiking, and adventure tours), outdoor event planning and catering are also subject to outdoor temperature. Unfortunately, we do not have more granular data to verify this potential effects.

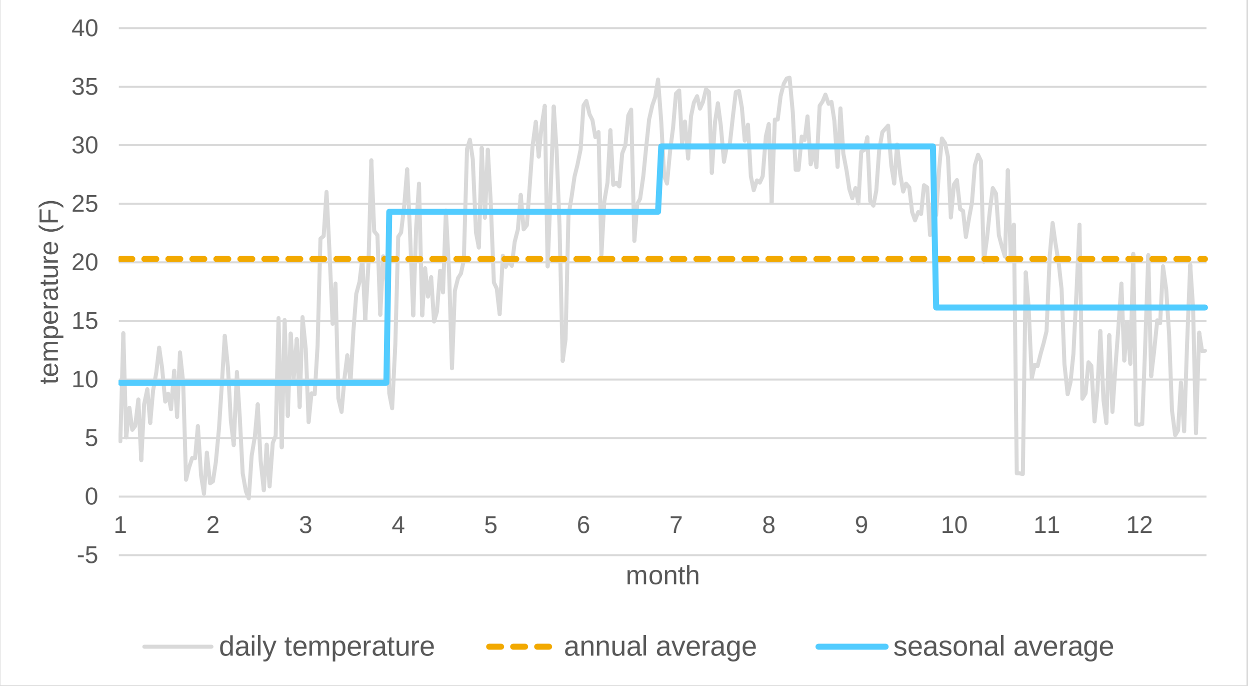


Figure 1: Washington D.C. temperature in 2021.
Source: ERA5 and authors' calculations

It is useful to note that the paper examines the short-term effects (up to four quarters) of a temporary shock in temperature. An important point of discussion is how these findings on short-term responses would help us predict the long-term responses to hotter climates. It has been argued that the short-run responses to temperature fluctuations are likely not the same as the long-run responses to climate change (see the discussion in Burke and Emerick, 2016, for example). First, the future magnitude of climate change is uncertain, depending on humankind's mitigation efforts. In addition, there could be a role of adaptation. Adaptation efforts, such as more widespread use of drought-resistant seeds or air-conditioning, might soften the impact of rising temperature in the future. If so, the short-run impacts may overstate the long-run impacts of climate. Conversely, the rising temperature may cause irreversible long-run effects on growth (such as capital and labor reallocation away from one sector depressing that sector's long-run growth, or emigration from one country depressing the country's long-run growth). In that case, the short-term impacts of temperature fluctuation might understate the long-run impacts of climate change.

This paper contributes to the discussion about the effects of climate change, by showing the impacts by decades. It finds that the impact of hotter seasonal temperature is getting worse for countries in recent decades. The worsening impacts of hotter seasonal temperature for AEs are especially significant, large, and consistent across seasons, and were largely driven by services. The worsening impacts for EMDEs is less significant and mostly driven by higher spring temperature. If taking the finding at face value, it suggests human's adaptation to changing weather conditions are not taking place in earnest or at least are not effective yet, leading to increasing economic costs from rising temperatures, especially in AEs.

The paper is organized as follows. Section II presents a simple theoretical framework to motivate the empirical specification. Section III presents data and the main empirical specification. Section IV presents the main findings on the overall impacts. Section V presents the effects by decade. Section VI presents robustness checks. Section VII concludes.

II. A Theoretical Framework

This section presents a theoretical motivation for the empirical setup, based on Dell et al. (2012). The framework assumes that temperature can have both a growth effect and a level effect on growth. Seasonal temperature first can affect economic activity through a level effect:

$$Y_{s,q} = e^{\beta_s T_q} A_{s,q}^{\alpha} \quad (1)$$

where $Y_{s,q}$ is sector s' value-added at quarter q; T_q is temperature of quarter q; $A_{s,q}$ is sector s' productivity at quarter q. The framework abstracts from capital and labor for simplicity.

In this simple setting, β_s captures the level effect of seasonal temperature; with β_s>0 implying that temperature T_q has a positive level effect on value-added. Note that β_s is season-specific and sector-specific. For example, the value for β_s might be negative for the spring and positive for the summer, and these effects may vary if, for example, we focus on agriculture or services.

Second, seasonal temperature can also affect economic activity through a growth effect:

$$\log(A_{s,q}) - \log(A_{s,q-4}) = g + \lambda_s T_q + \sigma_s T_{q-4} \quad (2)$$

Equation (2) states that year-on-year seasonal productivity growth depends on this quarter's temperature T_q as well as the temperature of the same season last year, T_{q-4} (4 quarters ago). λ_s represents the (growth) effect of temperature on the year-on-year seasonal productivity growth.

Combining (1) and (2), *yoy* growth in value-added equals:

$$log(Y_{s,q}) - log(Y_{s,q-4}) = \alpha g + (\beta_s + \alpha\lambda_s)T_q + (\alpha\sigma_s - \beta_s)T_{q-4} \quad (3)$$

The theoretical model suggests that the empirical specification should include at least the temperature of the current season (T_q) and the temperature of the same season last year (T_{q-4}). We are interested in estimating $(\beta_s + \alpha\lambda_s)$ which captures both the level and growth effects of seasonal temperature on economic activity.

In a special case, if assuming no growth effects of temperature, i.e., λ_s= σ_s=0, equation (3) becomes

$$log(Y_{s,q}) - log(Y_{s,q-4}) = \alpha g + \beta(T_q - T_{q-4})(4)$$

Equation (4) implies that year-on-year value-added growth is a function of the year-on-year change in temperature. (4) is a special case of (3) because it assumes no growth effects of temperature.

III. Data and Empirical Specification

Data

Real Quarterly Value-added: We collect real quarterly value-added of agriculture, manufacturing and services. The source is Haver Analytics' quarterly national accounts data. The dataset comprises 74 countries with available quarterly data, of 30 are AEs and 44 are EMDEs. Time coverage spans the 1990-2019 period (we drop pandemic years, due to large swings in value-added growth). We also winsorize top and bottom 1% of YoY growth in value-added to remove large swings in value-added growth.

Real Quarterly GDP: in additional to real quarterly value-added, we also collect real quarterly GDP from Haver Analytics. Quarterly GDP data is available for 87 countries, of which 30 are AEs and 57 are EMDEs. Data are also between 1990-2019. We also winsorize top and bottom 1% of YoY GDP growth. The lists of countries with Real Quarterly Value-added and Real Quarterly GDP data are in Annex 1.

Note that real quarterly value-added data are available for a smaller set of countries compared to quarterly GDP. In both cases, the set of countries is much smaller that the set of countries with available annual data, and, on average, are richer countries since poorer and smaller EMDEs do not typically report quarterly statistics. In this sense, the results in this paper are expected to represent lower bounds on the impact of temperature on growth, as it is reasonable to expect that impact on poorer and smaller EMDEs to be larger compared to those seen in the countries in our dataset.

Note also that we do not have data on value-added of construction in our dataset. Given construction's characteristics (i.e., the sector operates mostly outside), it is likely particularly vulnerable to weather shocks. Using data for US counties, Nguyen (2024) shows that the impact of rising temperature on construction could be particularly severe.

Table 1 provides summary statistics for YoY growth in real sectoral value-added and GDP (after winsorization). The median growth is about 2.1 to 3.5 percents a year, depending on the variable. Services have larger median growth in real value-added (3.44) than manufacturing (2.97) and agriculture (2.14).

Table 1: Summary Statistics for growth in real quarterly value-added and GDP, 1990-2019

YoY Growth (%)	Number of countries	Min	p1	p25	Median	p75	p99	Max
Agriculture value-added	74	-26.418	-19.654	-2.561	2.138	5.722	27.206	36.047
Manufacturing value-added	74	-15.397	-12.134	0.105	2.971	6.261	19.132	22.285
Services value-added	74	-6.857	-4.573	1.776	3.443	5.551	14.001	17.768
(Agri+Man+Serv) value-added	74	-7.659	-5.126	1.692	3.340	5.349	12.285	14.437
GDP	87	-9.014	-6.309	1.623	3.528	5.615	12.334	14.100

Seasonal temperature: temperature data are from ERA5 (Hersbach et al, 2023), which is the latest climate reanalysis produced by ECMWF (European Centre for Medium-Range Weather Forecasts) providing hourly data on many atmospheric, land-surface and sea-state parameters at high-spatial resolution (about 30 km by 30 km grid). The data are publicly available. Via the platform Google Earth Engine, we collect *maximum* daily temperature data from ERA5 between 1980 and Q2 of 2020 (ERA5 data are only available to July 9, 2020). Then, temperature is averaged across gridcells within a country to construct daily temperature data at the country level. Next, temperature is averaged across days to generate temperature at the quarterly frequency. In other words, we generate the seasonal mean of daily maximum temperature. Temperature is in Celsius.

To match temperature data with quarterly economic activity data, the analysis denotes average temperature for Quarter 1 (from January to March) as winter temperature, the average temperature for Quarter 2 (from April to June) as spring temperature, the average temperature for Quarter 3 (from July to September) as summer temperature, the average temperature for Quarter 4 (from October to December) as fall temperature. For the Southern hemisphere with the opposite seasoning pattern, winter is assigned from July to September, spring is from October to December, summer from January to March and fall from April to June.

Precipitation data: Precipitation data are collected similarly to the way temperature data are collected. First, total daily precipitation data by grids are collected from ERA5, then averaged across grids within a country and across the days within a season to generate seasonal average precipitation for country.

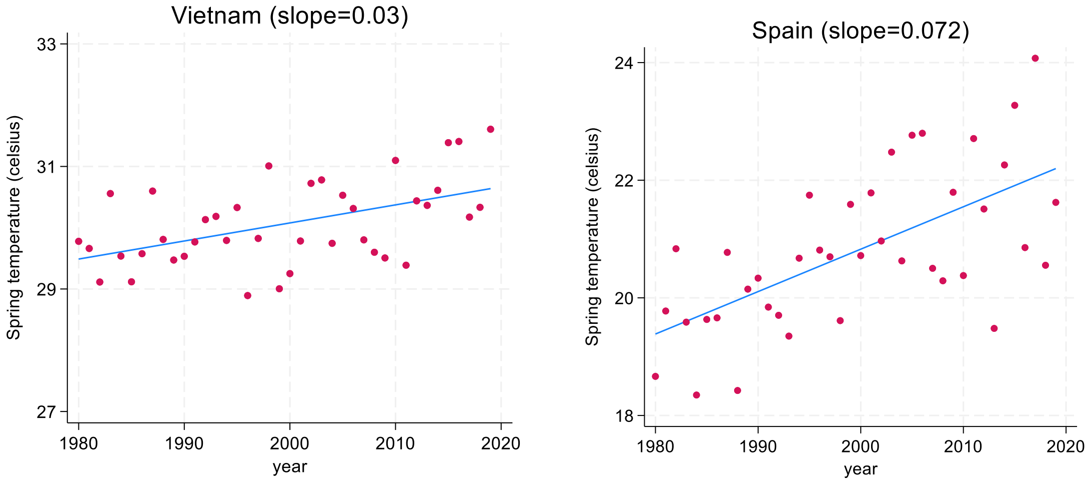
Table 2 shows summary statistics for temperature and the YoY change of temperature by season. On average, between 1980 and Q2 of 2020, temperature typically increases by about 0.028 to 0.031 Celsius degrees a year depending on the season (see the Median column). That translates to about 1.2 Celsius degrees for 40 years.

Table 2: Summary Statistics for temperature , 1980-Q2 2020

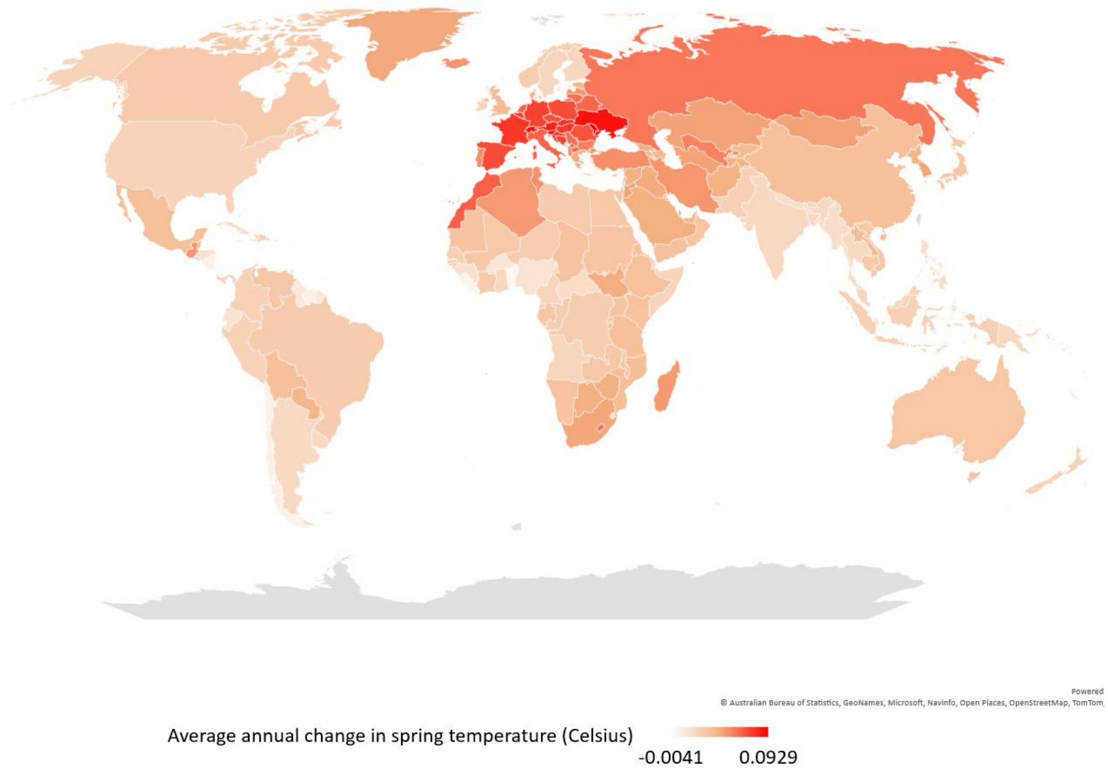
		No of countries / territories	Min	p1	Median	p75	p99	Max
Temperature Level (Celsius)	Winter (Q1)	219	-30.92	-15.12	25.08	27.84	35.42	38.23
	Spring (Q2)	219	-15.54	4.39	27.16	30.01	39.08	40.76
	Summer (Q3)	219	-8.40	10.57	27.80	29.85	40.96	46.20
	Fall (Q4)	219	-25.01	-9.49	25.77	28.04	33.81	35.71
YoY Change in Temperature (Celsius)	Winter (Q1)	219	-7.338	-3.794	0.028	0.640	4.344	7.500
	Spring (Q2)	219	-4.994	-2.632	0.031	0.545	2.673	4.475
	Summer (Q3)	219	-4.679	-2.701	0.031	0.464	2.794	4.771
	Fall (Q4)	219	-6.188	-3.269	0.031	0.557	3.119	6.629

Figure 1. Global Temperature Changes

Panel A: Average annual change in spring temperature for Vietnam and Spain



Panel B. Average annual change in spring temperature



To visually illustrate the change in seasonal temperature across countries, we select the spring temperature[4] and for each country, we run the following regression:

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[4] As will be clear, the spring temperature matters more for economic activity than other seasons' temperature.

$$\boldsymbol{Temp_{spring,c,year} = \alpha + \delta Year + \epsilon_{c,t}} \quad (\mathbf{5})$$

where $\boldsymbol{\delta}$ captures the average yearly increase in spring temperature within a country. This regression mitigates the influence of temperature at the start and end years in computing the average annual increase. Panel A of Figure 1 illustrates the average yearly increase in spring temperature for Vietnam and Spain. Vietnam has a slope of 0.03, that is, the average yearly increase is 0.03 Celsius degrees, or about 1.2 Celsius degrees in 40 years. Spain has a steeper slope (0.072), that is, the average yearly increase is 0.072 Celsius degrees, or about 2.9 Celsius degrees in 40 years. Panel B of Figure 1 shows such average yearly increases for all countries and territories in the world. Europe, interestingly, has larger yearly increases in spring temperature.

Empirical Specification

Guided by the theoretical framework, we follow the local projection method first introduced by Jordà, 2005 to estimate the dynamic impact of temperature.

$$\Delta(\boldsymbol{VA})_{\boldsymbol{q+h,c,s}} = \boldsymbol{\alpha} + \boldsymbol{\beta_{s,h}} \boldsymbol{Temp_{q,c}} + \boldsymbol{X_{q,c,h}} + \boldsymbol{fe_c} + \boldsymbol{fe_q} + \boldsymbol{\epsilon_{q,c}} \ (\mathbf{6})$$

Our empirical framework exploits a country-sector-quarterly panel, where $\boldsymbol{q}$ stands for quarter, $\boldsymbol{c}$ is for country, and $\boldsymbol{s}$ is for sector. We would like to estimate the impact of quarter $\boldsymbol{q}$'s temperature on *yoy* growth in sectoral value-added of quarter $\boldsymbol{q}$, and that of up to three quarters ahead $\boldsymbol{q+h}$ $(\boldsymbol{h = 1,2,3})$ **.** The dependent variable $\Delta(\boldsymbol{VA})_{\boldsymbol{q+h,c,s}}$ is sector $\boldsymbol{s}$' *yoy* quarterly value-added growth of quarter $\boldsymbol{q+h}$**.** Again, *yoy* growth in value-added is the growth rate between in value added in a given season in two consecutive years (e.g., between the value-added of this year's summer and the value-added of last year's summer). $\boldsymbol{Temp_{q,c}}$ is country $\boldsymbol{c}$'s average temperature in quarter $\boldsymbol{q}$. $\boldsymbol{\beta_{s,h}}$ is the effects of this quarter's temperature on YoY growth in value-added of quarter $\boldsymbol{q+h}$.

$\boldsymbol{X_{q,c,h}}$ is a list of controls. It has the following components:

- Temperature: $\boldsymbol{Temp_{q+j,c}}$ $(\boldsymbol{j = -4,-3,-2,-1,1,..,h})$. Note that we control for temperature of up to four quarters before quarter $\boldsymbol{q}$, and temperature of up to $\boldsymbol{h}$ quarters after quarter $\boldsymbol{q}$**.**[5] The idea is that to capture the impact of quarter $\boldsymbol{q}$**'**s temperature on *yoy* growth in value-added of quarter $\boldsymbol{q+h}$, we control for temperature of quarters $\boldsymbol{q+1, q+2 \ldots, q+h}$**.**
- Precipitation: $\boldsymbol{Prec_{q+j,c}}$ $(\boldsymbol{j = -4,-3,-2,-1,0,1,..,h})$. We control for precipitation of up to four quarters before quarter $\boldsymbol{q}$ and up to $\boldsymbol{h}$ quarters after quarter $\boldsymbol{q}$. Precipitation is an important control, especially for agriculture.
- Lagged growth in value-added. We control for lagged *yoy* growth in value-added up to four quarters before quarter $\boldsymbol{q}$: $\Delta(\boldsymbol{VA})_{\boldsymbol{q+j,c,s}}$ $(\boldsymbol{j = -4,-3,-2,-1})$

Finally, we include country fixed effects $\boldsymbol{fe_c}$ to capture country-specific long-run growth. Country-fixed effects will also control for systematic, time-invariant biases when aggregating sub-national temperature to the national level. We include year-quarter fixed effects $\boldsymbol{fe_q}$ to capture global shocks for each quarter from 1990 until 2019. Regressions are run for each of the sector (agriculture, manufacturing and services) individually.

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[5] Recent literature has highlighted the difference between weather and climate by distinguishing between temperature levels and deviations relative to long-term trends (see Kahn et al., 2021). The relative short time series dimension of our sample implies that our analysis will mostly focus on the impact of changes in seasonal temperature relative to country averages.

IV. Main Findings

Figure 2 shows the dynamic impact of higher seasonal temperature (1-Celsius degree) on *yoy* growth of sectoral value-added in agriculture, manufacturing and services. The left column shows estimates for advanced economies (AEs); the right column shows estimates for emerging markets and developing economies (EMDEs). Shaded areas show 90% confidence intervals. To compare magnitudes, all subfigures have the same scale.

Note that distinguishing effects by income group is important for several reasons. First, it helps study whether the potential economic drag of rising temperatures is shared equally between advanced economies and emerging markets, a topic of current debate.[6] Second, conditioning for differences in levels of development can help proxy for other structural/institutional variables mediating the impact of temperature shocks on economic activity (financial depth, fiscal space, etc).

For EMDEs, a 1-Celsius degree hotter spring reduces *yoy* growth in agricultural value-added in the same quarter by about 0.8 percentage points. It also reduces *yoy* growth in agricultural value-added for the following fall and winter by more than 1 percentage point. This is a very large impact.[7] A hotter summer also has a contemporaneous adverse effect on agricultural growth, with adverse impacts also manifesting in subsequent season (fall) (about 1 percentage points decline in yoy growth). By contrast, a 1-celsius degree warmer winter increases growth in agriculture’s value-added, but the impact is less statistically significant. [8]

Turning to AEs, a 1-Celsius degree hotter spring reduces *yoy* growth in agricultural value-added in the same season and the following one. However, the magnitude is smaller compared to that for EMDEs. A hotter summer also reduces agricultural growth in that summer and the following fall. Interestingly, a 1-Celsius degree warmer winter increases growth in agriculture’s value-added quite significantly for AEs and the impact is persistent for three quarters (until the following summer).

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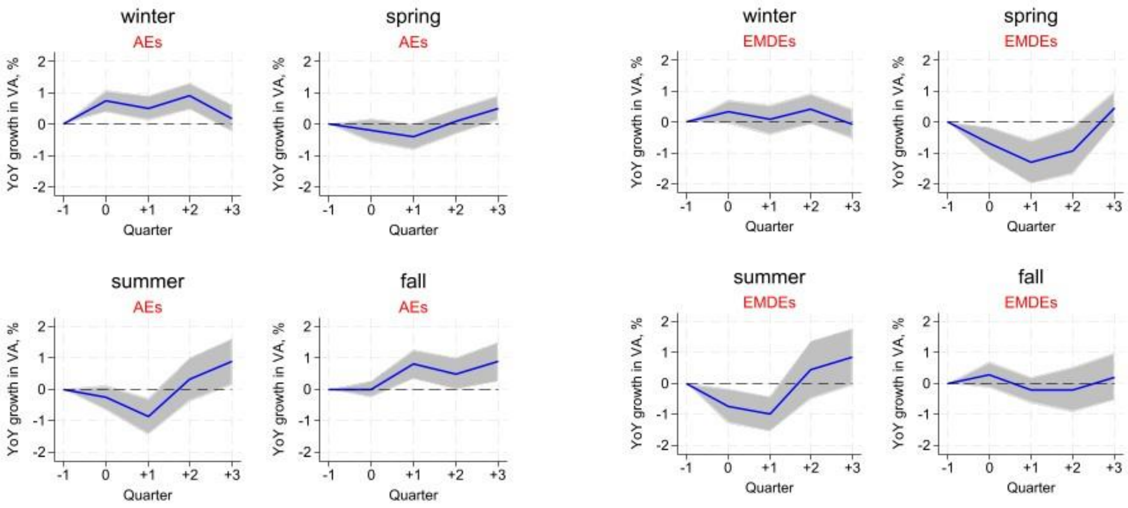
[6] World Bank (2023)

[7] For example, Dell et al. (2012) report that on average, across all countries, a 1 C increase in temperature reduces a country’s annual GDP growth by 0.3 percentage points and the decline is not statistically significant.

[8] Note that our sample of countries includes countries that are close to the equator, where differences in temperatures across seasons are less pronounced and the agricultural cycle is not as closely associated with seasonal patterns as in more temperate countries. To take this into account, we conduct robustness exercises that exclude countries with latitude below 5 and 10 degrees in absolute value. Results are virtually unchanged.

Figure 2: Dynamic impact of a 1-Celsius degree higher seasonal temperature on yoy growth of sectoral value-added

Panel A: Agriculture



Panel B: Manufacturing

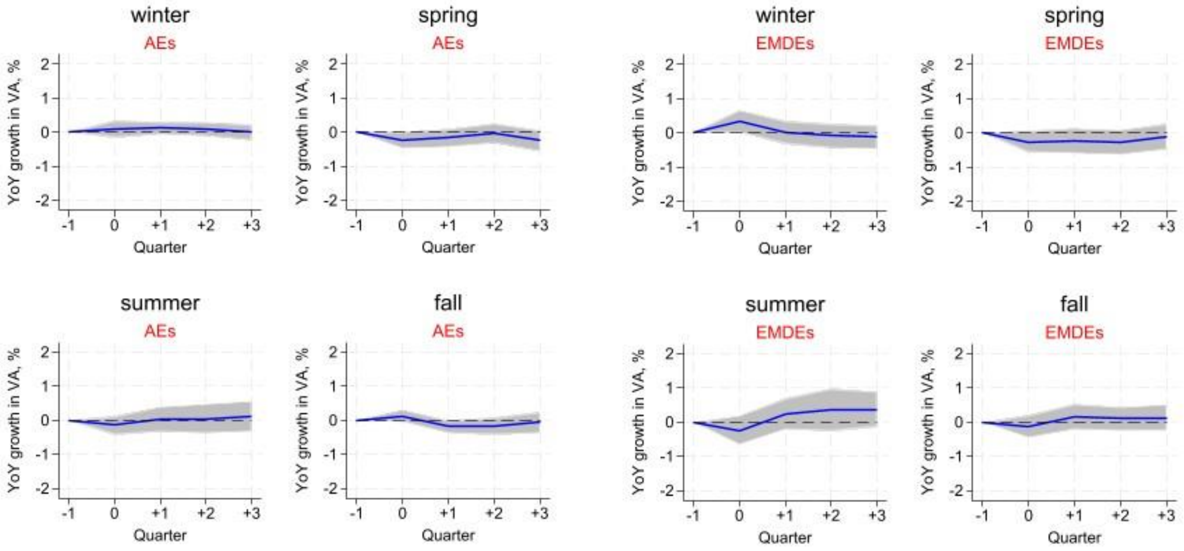
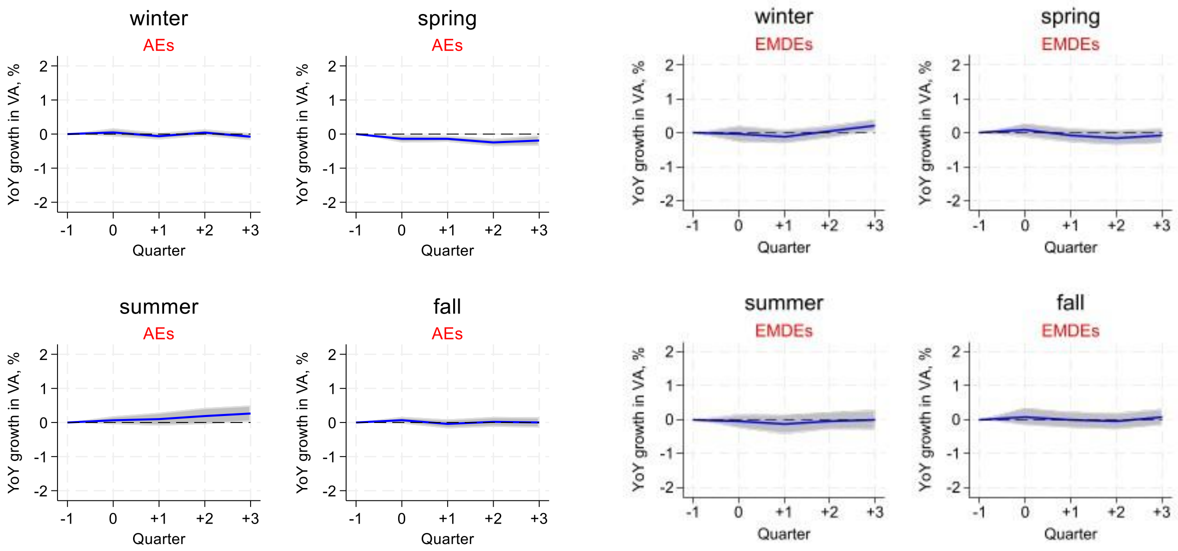


Figure 2: Dynamic impact of a 1-Celsius degree higher seasonal temperature on yoy growth of sectoral value-added (continued)

Panel C: Services



Notes: This figure shows estimates $\beta_{s,h}$ of equation (6). The left column shows estimates for advanced economies (AEs). The right column shows estimates for emerging markets and developing economies (EMDEs). Shaded areas show 90% confidence intervals. All subfigures have the same scale.

Why hotter temperature in the spring hurts growth in agriculture's value-added, not only for those seasons but also for subsequent seasons? Spring provides good conditions for planting and crop growth because of ideal temperature, water and rainfall and pollination (see Battey, 2000 and references therein). High temperatures cause an array of morpho-anatomical, physiological and biochemical changes in plants, which affect plant growth and development (Wahid et al. 2007). A hotter than usual spring may cause heat stress on plants, such as wilting, dehydration or even scorching of plant tissues. Heat also reduces plants' ability to photosynthesize. A hotter spring increases evaporation, resulting in the loss of soil moisture, leading to drought-like condition (Hatfield and Prueger, 2015). A hotter spring also causes increased weeds and pests and reduced pollination (e.g., bees), and weeds and pests are often more heat-tolerant and can thrive and become more resistant to herbicide in hot temperature (Matzrafi et al, 2016).

Similarly, a hot summer is, for many crops, harvesting season. This means that weather shocks, such as hotter-than-expected temperatures, can affect harvesting plans and affect the production of the agricultural sector. Our results are in line with Crofils, Gallic, Vermandel (2024), which focus on agriculture in Peru, and Hartfield and Prueger (2015) which conduct an experiment in a rhizotron facility and find that extreme temperature can have adverse growth effects when they occur during harvesting season. Moreover, as in Crofils, Galic, and Vermandel (2024), our results indicate that, especially in EMDEs, hotter springs yield more protracted growth effects.

Beyond agriculture, higher temperature also affects other sectors, albeit to a smaller degree. In the case of manufacturing, hotter springs and summers yield lower *yoy* growth in both AEs and EMDEs, although summer effects are not statistically significant. Moreover, the effects are substantially smaller compared to those in agriculture and tend to be short-lived. As in the case of agriculture, hotter winters appear to boost manufacturing growth.

Several factors could explain the link between higher temperatures and seasonal sectoral growth documented in Figure 2. First is a direct effect. The adverse impact of hot springs and summers can also be attributable to a worsening of working conditions in manufacturing plants, which could affect labor productivity. For example, Somanathan et al. (2021) find that hot days are associated with lower worker productivity and higher absenteeism. This problem could be particularly acute in countries with worse infrastructure (e.g., low levels of temperature control such as heat or air-conditioning). This would explain the larger negative effects of a hotter summer and a larger positive effect of a warmer winter for manufacturing in EMDEs relative to AEs. Second is a potential indirect effect. An important share of manufacturing activities is associated with agricultural production, especially in EMDEs, which means that the adverse impact of temperatures on agricultural growth can spillover to the manufacturing sector. This would explain, for example, the seasonal pattern of effects, whereby hotter winter has a positive impact on both manufacturing and agriculture, and hotter spring/summer has the opposite effects on both sectors.

Hotter temperatures have the lowest impact on services (Figure 2). The relatively insignificant impacts of temperature on service value-added could reflect the fact that much of service-related activities occur indoors. For EMDEs, in most seasons, hotter temperatures have a non-significant impact on service value-added yoy growth. However, in AEs, a hotter spring hurts yoy growth in services not only in the spring but also in subsequent seasons. The impact is small but statistically significant. Unlike EMDEs, in AEs, the gardening and landscaping industry is popular during the spring season. As the weather becomes more favorable for plant growth, many households seek professional assistance for planting flowers, maintaining lawns and other yard work. A hotter spring may dampen growth of this industry. Other services such as outdoor recreation (for example, bike and boat rentals, outdoor hiking, and adventure tours), outdoor event planning and catering are also subject to outdoor temperature. Unfortunately, we do not have more granular data to verify this potential effects.

To summarize, for emerging markets and developing countries (EMDEs), hotter spring and summer reduce growth in real value-added of manufacturing, and most significantly, of agriculture. But a warmer winter boosts it. For advanced countries (AEs), a hotter spring hurts growth in real value-added of all considered sectors: services, manufacturing and agriculture. A warmer winter also boosts growth in agriculture. However, since agriculture is small in AEs, a warmer winter turns out having negligible impact on the aggregate economy.

Figure 3 shows the dynamic impact of a 1-Celsius degree higher seasonal temperature on yoy growth of aggregate value-added (the sum of value-added in agriculture, manufacturing and services) and GDP. Note that for the regression for GDP, we would like to keep the sample size as consistent with that of the sectoral analyses. Hence, the sample of the regression for GDP consists of countries with both value-added and GDP data (27 AEs and 42 EMDEs). It is almost identical to the sample of sectoral analyses (which has 30 AEs and 44 EMDEs) (please see Annex 1 for more detail about country composition).

What stands out from Figure 3 is the negative impact of a hotter spring for both AEs and EMDEs. For EMDEs, a hotter spring reduces *yoy* growth in aggregate value-added contemporaneously and that in the following season (summer). Only in the following fall does the impact of temperature on *yoy* growth becomes significantly insignificant. For AEs, a hotter spring seems to have even more persistent effects because it affects all considered sectors. A hotter spring reduces *yoy* growth in aggregate value-added for the same spring and for all the three subsequent seasons we analyze. In other words, the impact is very persistent. None of other seasons see such a clear and significant effect of hotter temperature that the spring has. At peak, the magnitude of the negative spring aggregate effect is quite similar for EMDEs and AEs.

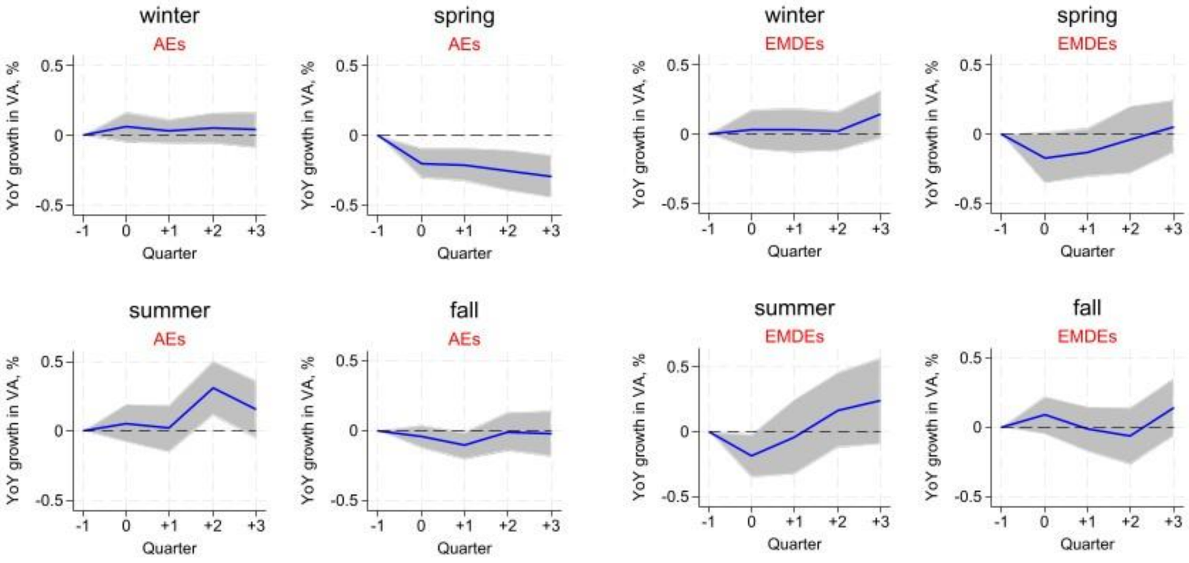
We confirm the results by examining GDP growth for AEs and EMDEs. A very similar finding emerges. A hotter spring reduces *yoy* growth in real quarterly GDP only in the spring but also for subsequent seasons. The effects are more persistent for AEs.

V. Impacts by Climate Zones and by Decades

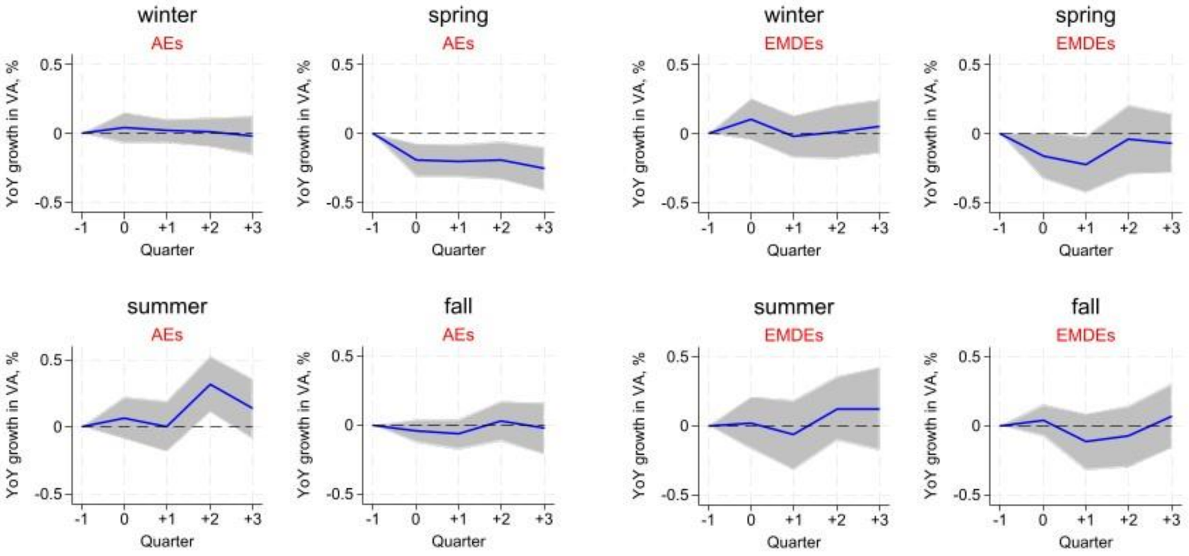
In this section we explore two important extensions to our baseline results. First, we assess how the relationship between seasonal temperature and economic activity is affected by a country’s level of development and geographic characteristics. We extend our econometric framework to control for both income levels and a country’s latitude, two variables potentially linked to a country’s resilience to climate shocks. Second, we explore how the relationship between seasonal temperature and growth has changed over time. This may be an important consideration amid secular changes in weather patterns globally.

Figure 3: Dynamic impact of a 1-Celsius degree higher seasonal temperature on yoy growth of aggregate value-added (agriculture+ manufacturing + services) and GDP.

Panel A: Aggregate (Agriculture +Manufacturing +Services)



Panel B: GDP



Notes: This figure shows estimates $\beta_{s,h}$ of equation (6). The left column shows estimates for advanced economies (AEs). The right column shows estimates for emerging markets and developing economies (EMDEs). Shaded areas show 90% confidence intervals. All subfigures have the same scale. The sample of GDP consists of countries with both value-added and GDP data (27 AEs and 42 EMDEs)

Income and Geography

An important finding obtained in the literature is that the impact of hotter temperature is more severe for hotter and poorer countries (e.g., Burke et al., 2015). Given this, we explore whether differences in the impact of seasonal between AEs and EMDEs are related to the geographic location of countries or is just a reflection of their level of development. To do so, we extend equation (6) by including two interactions. The first is an interaction between an AE dummy and temperature. The second is an interaction between a tropical country dummy and temperature. Tropical countries are defined as countries located south of the Tropic of Cancer and north of the Tropic of Capricorn.[9] The idea is to include both interactions in the same regression to isolate the effect of the level of development when assessing the impact of a country's geographic location in the relationship between temperature and growth and vice versa. The econometric specification is as below:

$$\Delta(VA)_{q+h,c,s} = \alpha + \beta_{s,h} Temp_{q,c} + \gamma_{s,h} Temp_{q,c} \times Tropics + \delta_{s,h} Temp_{q,c} \times AEs + X_{q,c,h} + fe_c + fe_q + \epsilon_{q,c} \quad (7)$$

The two coefficients of interest are $\boldsymbol{\gamma_{s,h}}$ and $\boldsymbol{\delta_{s,h}}$**,** the interactions between temperature and the tropics dummy and between temperature and the AEs dummy. Table 3 shows results for the extended econometric specification.

Results show that, from the point of view of aggregate value-added growth, AEs do not appear to be more resilient to higher temperature than EMDEs, *after controlling for climate zone*. All the interactions *AEs*temperature* are either not significantly different from zero, or in some cases negative (see Panel A of Table 3).

This is not the case for agriculture, where AEs fare better than EMDEs once we control for countries' geographic location. Some interactions *AEs*temperature* for spring and fall temperature are significant and positive, implying that the same 1-Celsius degree increase in seasonal temperature yields less negative impact on agricultural value-added for AEs than for EMDEs (Panel B of Table 3). However, due to the small share of agriculture in AE's economy, the differential impacts for agriculture value-added do not translate to the aggregate value-added.

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[9] The Tropic of Cancer is located at approximately latitude 23°27′ N of the terrestrial equator and the Tropic of Capricorn is located at latitude 23°27′ S.

Table 3: The dynamic impact of 1-Celsius degree hotter seasonal temperature on aggregate value-added and agricultural value-added.

Panel A: Aggregate (Agriculture + Manufacturing + Services)

Season	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.143	-0.0769	-0.0307	0.126	0.0858	-0.005	-0.11	0.154	-0.181*	-0.0268	0.176	0.256	0.0444	0.0182	0.0308	0.128
	-0.123	-0.119	-0.169	-0.113	-0.0842	-0.0994	-0.13	-0.132	-0.108	-0.183	-0.182	-0.211	-0.0902	-0.102	-0.0928	-0.113
AEs*temperature	-0.0228	-0.0302	-0.11	-0.299**	-0.0536	-0.0971	0.116	-0.126	0.14	-0.0168	0.00611	-0.0196	-0.0176	-0.024	-0.00829	-0.113
	-0.119	-0.126	-0.177	-0.118	-0.0942	-0.111	-0.136	-0.143	-0.115	-0.193	-0.184	-0.221	-0.101	-0.095	-0.105	-0.116
Tropics*temperature	-0.154	-0.333*	-0.057	-0.449**	-0.00287	-0.103	0.419	-0.121	-0.0759	-0.176	-0.132	-0.25	-0.0938	0.127	-0.0745	0.156
	-0.165	-0.185	-0.233	-0.208	-0.345	-0.418	-0.296	-0.38	-0.275	-0.36	-0.429	-0.358	-0.225	-0.26	-0.216	-0.215
Constant	1.705	3.105	3.551	-1.313	0.337	-3.252	0.256	-1.723	1.139	2.143	-6.58	3.983	-1.251	1.492	1.887	1.557
	-2.99	-3.552	-4.132	-5.521	-2.573	-3.635	-4.424	-4.931	-2.807	-3.538	-5.098	-4.604	-3.683	-3.666	-4.281	-5.372
Observations	1,271	1,270	1,268	1,196	1,214	1,207	1,205	1,200	1,279	1,275	1,205	1,204	1,273	1,271	1,262	1,262
R-squared	0.797	0.693	0.580	0.516	0.755	0.635	0.568	0.503	0.774	0.656	0.579	0.523	0.658	0.617	0.576	0.502

Panel B: Agriculture

Season	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.580*	-1.519***	-1.179**	0.521	0.299	-0.197	-0.0770	0.398	-0.760**	-1.002***	0.487	0.864	0.300	0.114	0.448	-0.111
	(0.317)	(0.457)	(0.483)	(0.348)	(0.281)	(0.273)	(0.464)	(0.486)	(0.357)	(0.353)	(0.596)	(0.587)	(0.248)	(0.317)	(0.314)	(0.312)
AEs*temperature	0.377	1.109**	1.257**	0.00022	-0.297	0.998***	0.578	0.480	0.499	0.137	-0.196	0.0103	0.431	0.404	0.452	0.280
	(0.336)	(0.502)	(0.545)	(0.373)	(0.331)	(0.359)	(0.540)	(0.607)	(0.417)	(0.457)	(0.624)	(0.605)	(0.313)	(0.397)	(0.387)	(0.424)
Tropics*temperature	-0.547	1.356**	1.518**	-0.382	-0.208	-0.245	-1.170	-1.714**	0.309	0.1000	-0.767	-0.154	0.420	-0.462	-0.149	0.601
	(0.515)	(0.620)	(0.753)	(0.921)	(0.395)	(0.709)	(0.884)	(0.833)	(0.471)	(0.494)	(0.896)	(0.981)	(0.367)	(0.681)	(0.626)	(0.485)
Constant	9.142	1.338	14.73	-28.54*	15.51*	-31.33***	-12.83	-6.583	8.940	21.95**	-31.30**	-24.39	-20.74*	-13.94	-2.997	11.73
	(10.05)	(10.80)	(11.59)	(15.48)	(8.157)	(11.49)	(17.63)	(15.26)	(9.584)	(10.23)	(15.30)	(22.25)	(11.18)	(14.47)	(12.76)	(11.70)
Observations	1,256	1,243	1,248	1,192	1,197	1,196	1,195	1,178	1,254	1,257	1,199	1,197	1,263	1,260	1,244	1,248
R-squared	0.628	0.506	0.464	0.224	0.599	0.254	0.244	0.275	0.633	0.522	0.236	0.242	0.284	0.245	0.267	0.250

Notes: The table presents the econometric results following equation (7). Robust standard errors in paratheses. * p<0.1, ** p<0.05, *** p<0.01

Changes over time

In addition, an important question is how the short-term relationship between temperature and growth can shed light on the long-run impact of climate change. We contribute to this question by examining the impact of seasonal temperature on growth by decade. We do so by splitting our sample into three periods: the 1990s (1990-1999), the 2000s (2000-2009) and the 2010s (2010-2019). We then interact the decadal dummy with temperature (see equation 8). Table 4 shows the findings.

$$\Delta(VA)_{q+h,c,s} = \alpha + \beta_{s,h} Temp_{q,c} + \gamma_{s,h} Temp_{q,c} \times 2000s + \delta_{s,h} Temp_{q,c} \times 2010s + X_{q,c,h} + fe_c + fe_q + \epsilon_{q,c} \quad (8)$$

For AEs, the adverse impact of a 1-Celsius increase in temperature on aggregate value-added growth is found to be more pronounced in last decade, 2010s, compared to the 1990s (Panel A of Table 4). The larger impact seen in recent years cuts across seasons: the interaction term *2010s*temperature* is largely negative and significant for all seasonal temperature. To confirm our results, we rerun the regression for real quarterly GDP growth. The same finding emerges (Table B of Table 4). Turning to specific sector, results indicate that the increasing impact of temperature on growth is largely driven by services (Panel C of Table 4). It is possible that the effect of a 1-Celsius temperature increase is becoming more severe as the weather gets hotter. It is also possible that the service sector in AEs is gearing to more outdoor-oriented industries and hence is more subject to temperature. This is the topic of future research.

For EMDEs, the impacts by decade are more localized to specific seasons. Table 5 shows that in EMDEs the impact of spring temperature on GDP growth has been more negative since the 2000s. This may be related to EMDE's relatively large dependence on agriculture, a sector that is more susceptible to spring shocks. We do not find statistically significant changes over time for other seasons, a pattern that differs relative to AEs.

The rising impact of seasonal temperature on economic activity found for AEs is consistent with findings for the US (Colacito et al., 2019, Nguyen, 2024). These results are indicative of limited improvements in climate resilience in the short-term and suggest that the economic impacts of hotter temperatures could ensue large economic costs. It also emphasizes the importance of investments in adaptation that help improve resilience to changing climate conditions.

Table 4: Impacts by decade for AEs

Panel A: Aggregate

	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.0590	-0.0600	-0.0679	-0.0486	0.0278	-0.101	0.0210	0.0205	-0.0163	-0.0486	0.144	0.215	-0.0228	-0.0788	0.0390	0.00134
	(0.0573)	(0.0530)	(0.0748)	(0.0948)	(0.0598)	(0.0767)	(0.0879)	(0.103)	(0.0590)	(0.101)	(0.133)	(0.154)	(0.0832)	(0.0738)	(0.0868)	(0.0861)
Temp*2000s	-0.0148	-0.00333	-0.00978	-0.00687	0.000912	-0.00855	-0.0503	-0.0339	0.0125	0.00359	-0.00490	-0.0521	-0.00669	-0.0263	-0.0319	-0.0193
	(0.0188)	(0.0219)	(0.0252)	(0.0410)	(0.0126)	(0.0243)	(0.0322)	(0.0362)	(0.0237)	(0.0272)	(0.0402)	(0.0459)	(0.0257)	(0.0376)	(0.0316)	(0.0343)
Temp*2010s	-0.0493***	-0.0536**	-0.0790***	-0.0754	-0.0263*	-0.0334	-0.0783**	-0.0823**	-0.0273	-0.0575*	-0.0689	-0.131***	-0.0202	-0.0455	-0.0622*	-0.0648*
	(0.0175)	(0.0231)	(0.0273)	(0.0446)	(0.0141)	(0.0248)	(0.0311)	(0.0344)	(0.0217)	(0.0291)	(0.0413)	(0.0447)	(0.0268)	(0.0361)	(0.0325)	(0.0353)
Constant	-1.845	-0.765	5.826	1.106	2.975*	1.187	4.199	4.829	-0.370	5.038*	-1.089	6.851	4.095	3.577	3.077	8.573**
	(2.190)	(3.535)	(3.522)	(4.820)	(1.713)	(3.223)	(3.806)	(4.209)	(2.653)	(2.660)	(4.340)	(4.852)	(2.774)	(3.277)	(3.915)	(4.015)
Observations	681	678	677	643	653	647	648	646	682	681	647	649	680	681	677	677
R-squared	0.849	0.767	0.672	0.582	0.814	0.693	0.637	0.585	0.853	0.733	0.634	0.593	0.732	0.675	0.637	0.575

Panel B: GDP

	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.133*	-0.118	-0.152	-0.126	0.0113	-0.0351	0.00452	-0.0744	0.0760	0.0494	0.353**	0.162	0.00646	-0.0387	0.0187	0.0386
	(0.0779)	(0.0814)	(0.0921)	(0.0836)	(0.0665)	(0.0838)	(0.0992)	(0.138)	(0.104)	(0.124)	(0.155)	(0.164)	(0.0716)	(0.0715)	(0.0813)	(0.128)
Temp*2000s	-0.0160	-0.00699	0.00879	0.0262	-0.00308	-0.0147	-0.0612**	-0.0700	0.00318	0.0111	0.0173	-0.0433	-0.0319	-0.0469	-0.0719*	-0.0537
	(0.0171)	(0.0316)	(0.0336)	(0.0407)	(0.0215)	(0.0278)	(0.0278)	(0.0460)	(0.0339)	(0.0316)	(0.0442)	(0.0479)	(0.0278)	(0.0282)	(0.0352)	(0.0482)
Temp*2010s	-0.0577***	-0.0467*	-0.0650*	-0.0481	-0.0273	-0.0389	-0.0674**	-0.0875**	-0.0227	-0.0525	-0.0522	-0.104**	-0.0456**	-0.0459*	-0.0717**	-0.0845*
	(0.0159)	(0.0244)	(0.0335)	(0.0403)	(0.0173)	(0.0229)	(0.0300)	(0.0336)	(0.0230)	(0.0311)	(0.0430)	(0.0428)	(0.0193)	(0.0257)	(0.0293)	(0.0419)
Constant	0.152	-3.008	2.319	-3.805	2.441	-2.411	8.220*	7.257	-3.889	2.123	-4.934	9.668*	1.222	5.960	1.837	7.661
	(3.291)	(5.169)	(4.156)	(4.982)	(2.306)	(3.173)	(4.649)	(4.675)	(4.182)	(2.504)	(4.452)	(5.257)	(3.061)	(4.098)	(4.844)	(4.510)
Observations	632	633	629	604	607	607	606	606	635	631	606	605	634	633	632	628
R-squared	0.805	0.751	0.633	0.633	0.795	0.742	0.660	0.593	0.821	0.705	0.681	0.590	0.784	0.694	0.650	0.561

Panel C: Services

	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.0528	-0.0924*	-0.177*	-0.123	0.0728	-0.0901	0.0633	-0.00336	0.098	0.0555	0.222	0.344**	0.00325	-0.0574	0.0687	-0.000758
	-0.0681	-0.0525	-0.0929	-0.102	-0.0805	-0.0732	-0.0755	-0.096	-0.0777	-0.11	-0.155	-0.159	-0.0843	-0.0803	-0.0892	-0.106
Temp*2000s	-0.0346	-0.0543	-0.0386	-0.0688	0.00504	-0.022	-0.0837**	-0.0841**	-0.0396*	-0.0162	-0.0493	-0.0973**	-0.00578	-0.0474	-0.0817**	-0.0547
	-0.0291	-0.0334	-0.0408	-0.0433	-0.0209	-0.0213	-0.0318	-0.0378	-0.0227	-0.0317	-0.0401	-0.0467	-0.0257	-0.0384	-0.0352	-0.0462
Temp*2010s	-0.0707**	-0.105***	-0.101**	-0.131***	-0.0241	-0.0446**	-0.110***	-0.127***	-0.0782***	-0.0713**	-0.121***	-0.174***	-0.0245	-0.0729*	-0.121***	-0.0978**
	-0.0292	-0.0333	-0.039	-0.0445	-0.0199	-0.0205	-0.0311	-0.0366	-0.0233	-0.0291	-0.038	-0.0456	-0.0265	-0.0369	-0.0381	-0.0459
Constant	-1.489	1.153	4.576	6.631	4.610**	2.947	5.462	8.884**	0.323	3.72	2.993	8.500*	4.178	3.32	5.511*	7.650**
	-1.945	-2.77	-3.429	-4.303	-1.774	-2.889	-3.633	-3.491	-2.125	-2.495	-3.84	-4.941	-2.693	-2.98	-2.816	-3.111
Observations	696	696	693	663	668	666	667	665	698	695	665	666	696	696	694	691
R-squared	0.797	0.696	0.625	0.557	0.783	0.687	0.624	0.543	0.773	0.7	0.594	0.555	0.721	0.667	0.593	0.55

Notes: The table presents the econometric results following equation (8). Robust standard errors in paratheses. * p<0.1, ** p<0.05, *** p<0.01

Table 5: Impacts by decade for EMDEs

Panel A: Aggregate

	spring	spring	spring	spring	fall	fall	fall	fall	summer	summer	summer	summer	winter	winter	winter	winter
temp	-0.154	-0.0950	-0.0770	0.0530	0.0484	0.0283	0.0502	0.285*	-0.231	-0.0539	0.107	0.457	0.0819	0.196	0.0862	0.160
	(0.155)	(0.133)	(0.168)	(0.190)	(0.0979)	(0.124)	(0.161)	(0.151)	(0.162)	(0.300)	(0.297)	(0.278)	(0.117)	(0.138)	(0.108)	(0.156)
temp*2000	-0.0946***	-0.0172	0.0191	0.0546	0.0559	0.0261	-0.0433	-0.0594	0.0455	0.0743	0.0740	0.0161	0.000411	-0.0851**	-0.0262	0.0182
	(0.0245)	(0.0755)	(0.111)	(0.143)	(0.0497)	(0.0786)	(0.0505)	(0.0767)	(0.0522)	(0.101)	(0.125)	(0.101)	(0.0471)	(0.0377)	(0.0499)	(0.0787)
temp*2010	-0.0733**	0.00110	0.0554	0.0451	0.0692	0.0416	-0.0179	-0.0228	0.0316	0.0490	0.00973	-0.0880	0.0382	-0.0366	0.0147	0.0519
	(0.0340)	(0.0693)	(0.0942)	(0.146)	(0.0441)	(0.0823)	(0.0502)	(0.0687)	(0.0627)	(0.118)	(0.155)	(0.134)	(0.0510)	(0.0432)	(0.0477)	(0.0673)
Constant	7.750	4.360	-3.055	-16.11	-7.186	-16.20*	-10.65	-21.12*	1.184	-4.568	-21.79*	-15.82	-14.90	-2.830	-3.046	-6.345
	(7.353)	(8.305)	(11.18)	(14.45)	(6.287)	(8.432)	(10.65)	(11.61)	(5.492)	(8.679)	(12.54)	(11.33)	(9.008)	(8.761)	(8.634)	(11.89)
Observations	590	592	591	553	561	560	557	554	597	594	558	555	592	589	584	584
R-squared	0.786	0.677	0.565	0.518	0.768	0.638	0.582	0.523	0.750	0.626	0.580	0.526	0.675	0.617	0.570	0.488

Panel B: GDP

	spring				fall				summer				winter			
Horizon	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
Temperature	-0.119	-0.171	0.0215	-0.0200	0.0751	-0.118	0.0133	0.230	0.117	0.0263	0.122	0.324	0.115	0.115	0.0804	0.00406
	(0.135)	(0.162)	(0.183)	(0.181)	(0.0802)	(0.154)	(0.182)	(0.198)	(0.175)	(0.279)	(0.233)	(0.266)	(0.105)	(0.107)	(0.130)	(0.136)
Temp*2000s	-0.168***	-0.168	-0.0290	-0.00487	0.0546	0.0547	9.22e-05	-0.0277	-0.0861	0.0630	0.0964	0.0692	0.0302	-0.0854*	-0.0923	0.0156
	(0.0602)	(0.127)	(0.123)	(0.134)	(0.0377)	(0.0492)	(0.0364)	(0.0708)	(0.103)	(0.148)	(0.104)	(0.0829)	(0.0287)	(0.0489)	(0.0668)	(0.0536)
Temp*2010s	-0.123*	-0.157	-0.0409	-0.00624	0.0632**	0.0598	0.00368	-0.0475	-0.0374	-0.0491	0.0312	-0.0533	0.0706*	-0.0407	-0.0627	0.0393
	(0.0628)	(0.121)	(0.115)	(0.150)	(0.0304)	(0.0535)	(0.0305)	(0.0611)	(0.105)	(0.146)	(0.147)	(0.106)	(0.0363)	(0.0459)	(0.0643)	(0.0477)
Constant	11.35	0.0949	-11.46	-13.14	-10.31	-17.04**	-7.055	-2.563	-5.837	-9.413	-25.06**	-4.280	-12.95*	-2.454	-6.482	-19.48
	(8.866)	(11.31)	(14.46)	(16.01)	(7.690)	(7.698)	(9.795)	(13.63)	(7.188)	(10.17)	(11.72)	(11.45)	(7.011)	(8.444)	(15.47)	(15.86)
Observations	581	579	577	544	553	556	552	550	586	581	550	547	584	582	576	573
R-squared	0.742	0.655	0.577	0.597	0.771	0.684	0.595	0.549	0.773	0.638	0.651	0.566	0.715	0.623	0.550	0.523

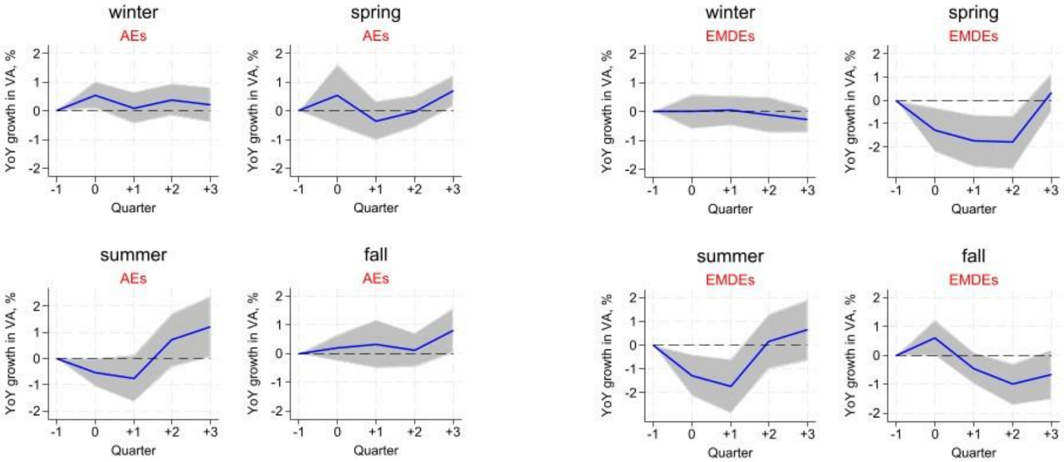
Notes: The table presents the econometric results following equation (8). Robust standard errors in paratheses. * p<0.1, ** p<0.05, *** p<0.01

VI. Robustness Checks and Extensions

This section presents two exercises assessing the robustness of our results. First, we include the top and bottom 1% of real value-added growth that we winsorize in the baseline sample. The idea is to examine if the result holds if all extreme growth data are included. Figure 4 shows that the overall findings largely hold, albeit with a large magnitude and larger standard errors. The hotter spring and summer temperature still hurts agricultural growth in EMDEs (but less so for AEs). For EMDEs, the magnitude of the impact on agriculture, which is close to 2%, is larger than that in the baseline. However, the standard errors are larger which is expected due to the inclusion of the extreme growth data. A hotter spring temperature hurts growth in services and manufacturing in AEs. This is largely consistent with the baseline findings.

Figure 4: Dynamic impact of a 1-Celsius degree higher seasonal temperature on yoy growth of sectoral value-added (no winsorizing)

Panel A: Agriculture



Panel B: Manufacturing

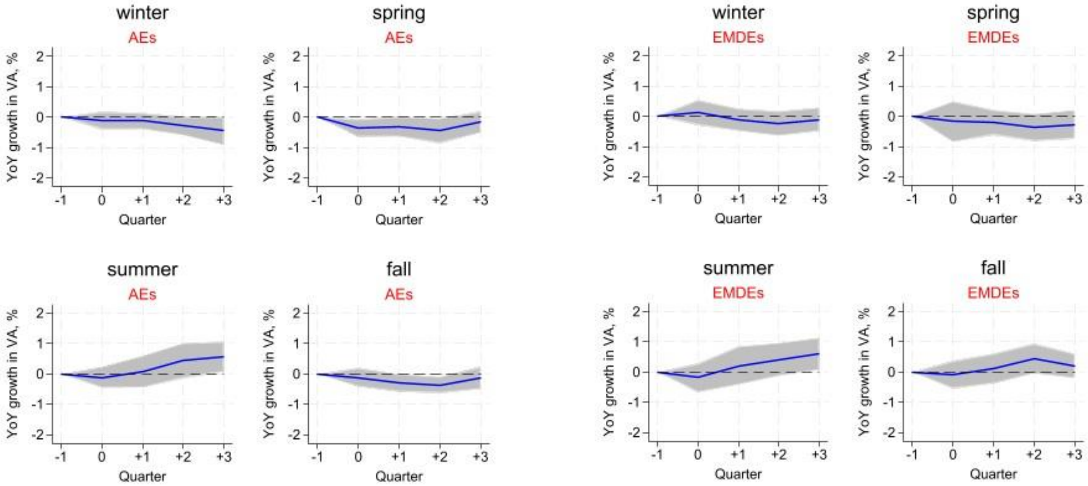
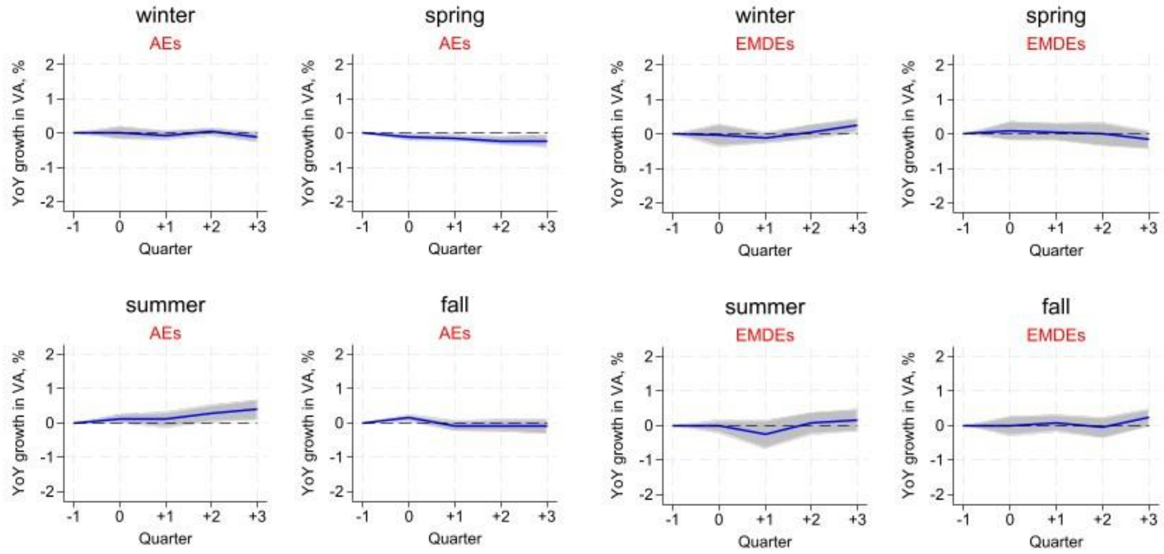


Figure 4 (continued): Dynamic impact of a 1-Celsius degree higher seasonal temperature on yoy growth of sectoral value-added (no winsorizing)

Panel C: Services



Notes: This figure shows estimates $\beta_{s,h}$ of equation (6). The left column shows estimates for advanced economies (AEs). The right column shows estimates for emerging markets and developing economies (EMDEs). Shaded areas show 90% confidence intervals. All subfigures have the same scale.

In the second robustness check, we control for lags of *yoy* growth in value-added up to four quarters of all sectors, namely manufacturing, services and agriculture. Note that in the baseline specification, only the lags of *yoy* growth in value-added of the corresponding sector to the dependent variable are included. The motivation for this robustness check is that in some countries, one sector's output can be an important input to another sector. For example, the industry sector, specially the agri-food industry, takes inputs from the agriculture sector. After we control for lags of *yoy* growth in value-added of all sectors, the quantitative results are unchanged. Hence, they are not shown here and are available upon request.

Next, we explore the potentially differential impact of extreme temperatures (i.e., above a country-season specific threshold) on economic activity. To do so, we expand our baseline specification as follows:

$$\Delta(VA)_{q+h,c,s} = \alpha + \beta_{s,h} Temp_{q,c} + \gamma_{s,h} Temp_{q,c} \times extreme\ heat_{q,c} + X_{q,c,h} + fe_c + fe_q + \epsilon_{q,c} \ (9)$$

where $extreme\ heat_{q,c}$ is a dummy variable that takes value one if the temperature in country c, in quarter q is above the 70th percentile of the country-quarter historical distribution.

Results in Table 6 show that extreme heat can yield larger declines in growth relative to intermediate temperature values in all sectors. The adverse consequences of extreme heat are most visible in agriculture, where extremely hot temperature in the spring, summer and fall leads to a more severe growth slowdown. In the case of manufacturing, extreme heat hurts value added growth in summers. This is consistent with recent literature showing that extremely hot temperature leads to more worker absenteeism and lower worker productivity in the manufacturing sector (see Rode et al. 2023). Conversely, extremely hot summer helps value-added growth in services, probably in activities that alleviate heat stress (such as indoor services or beach going).

VII. Conclusions

Using quarterly and sectoral data, this paper uncovers nuanced effects of temperature. It finds that, for EMDEs, hotter spring and summer temperatures reduce growth in real value-added of manufacturing, and most significantly, of agriculture—a 1-Celsius degree hotter spring reduces *yoy* growth in agricultural value-added in the same quarter by about 0.8 percentage points and by more than 1 percentage point for the following fall and winter. By contrast, a warmer winter boosts agricultural activity. For advanced countries (AEs), a hotter spring hurts growth in real value-added of all considered sectors: services, manufacturing and agriculture. Overall, for both country groups, the negative effect of a hotter spring is larger and more persistent than the positive effect of a warmer winter. For EMDEs, the more negative spring effect has to do more with agriculture and manufacturing while for AEs, it has to do with agriculture, manufacturing and services.

These results highlight the heterogeneous impacts that extreme temperatures could have across sectors. From a macroeconomic point of view, our results point to the importance of considering the timing of climate shocks and the sectoral composition of the economy when gauging the expected impacts of climate change. Our results also shed light on the likely uneven impacts of rising temperatures on the livelihoods of individuals. More precisely, the larger impact of higher temperatures on agriculture, where a large share of low-income workers are employed, point to the potentially adverse consequences of climate change on poverty and inequality.

Importantly, our results point to the potential risks for economic activity of a hotter world. First, we estimate that the impact of temperature on economic activity is mainly driven by extreme heat. Thus, all else equal, hotter seasons, especially above-mean temperatures are likely to have a particularly negative impact on economic activity. The potentially increasing economic costs of rising temperature is also indicated by the fact that the adverse impacts of hotter temperatures in advanced economies and to a less extent, EMDEs, have accentuated in recent decades. In the case of AEs, this is largely driven by services. This indicates that economies have become more susceptible to temperature over time. Most notably is the service sector in AEs. The finding emphasizes the importance of adjusting the economic structure and of investments in adaptation that help improve resilience to changing climate conditions.

Table 6: Impacts of Extreme Temperature

Panel A: Agriculture

	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.333	-0.561*	0.0625	0.880***	0.112	0.550**	0.451	0.782**	-0.375	-0.818**	0.735	1.241***	0.611***	0.364*	0.715***	0.0360
	(0.277)	(0.308)	(0.300)	(0.308)	(0.153)	(0.229)	(0.282)	(0.331)	(0.282)	(0.312)	(0.471)	(0.467)	(0.166)	(0.193)	(0.207)	(0.193)
Temperature*extreme heat dummy	-0.00533	-0.0215	-0.0442**	-0.0520**	-0.00681	-0.0286	-0.0571*	-0.0401	-0.00816	-0.0119	-0.0496**	-0.0484**	-0.0159	-0.0154	-0.00444	0.0212
	(0.0194)	(0.0176)	(0.0190)	(0.0242)	(0.0192)	(0.0244)	(0.0289)	(0.0281)	(0.0172)	(0.0243)	(0.0212)	(0.0220)	(0.0226)	(0.0247)	(0.0251)	(0.0264)
Constant	5.026	0.551	11.28	-37.83**	15.47*	-38.27***	-23.62	-19.12	7.321	19.98*	-42.76**	-33.31	-21.68*	-18.66	-5.287	13.44
	(9.703)	(11.95)	(11.52)	(15.92)	(8.339)	(10.06)	(16.45)	(15.15)	(11.30)	(11.30)	(16.90)	(22.97)	(11.11)	(14.28)	(12.55)	(10.88)
Observations	1,256	1,243	1,248	1,192	1,197	1,196	1,195	1,178	1,254	1,257	1,199	1,197	1,263	1,260	1,244	1,248
R-squared	0.627	0.504	0.462	0.227	0.599	0.250	0.243	0.273	0.632	0.522	0.239	0.245	0.283	0.244	0.266	0.250

Panel B: Manufacturing

	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.239	-0.240	-0.123	-0.221	0.0713	-0.0400	-0.0807	0.0726	-0.0350	0.257	0.347	0.469	0.154	0.0471	0.00818	-0.0723
	(0.156)	(0.176)	(0.178)	(0.206)	(0.0929)	(0.127)	(0.138)	(0.161)	(0.180)	(0.238)	(0.302)	(0.306)	(0.133)	(0.124)	(0.135)	(0.145)
Temperature*extreme heat dummy	-0.000335	0.00681	0.000259	0.00246	-0.00793	-0.00991	-0.00161	-0.0210	-0.0176*	-0.0182	-0.0237	-0.0321*	0.0171	0.00925	-0.000223	0.00496
	(0.0121)	(0.0144)	(0.0162)	(0.0182)	(0.0136)	(0.0164)	(0.0188)	(0.0188)	(0.00999)	(0.0139)	(0.0170)	(0.0186)	(0.0155)	(0.0150)	(0.0193)	(0.0207)
Constant	6.892	13.86	18.55*	7.554	-8.805**	-5.626	9.015	13.70	7.027	6.680	-4.126	8.679	7.675	11.91*	21.08**	22.70**
	(6.126)	(9.167)	(10.02)	(10.85)	(3.680)	(5.942)	(8.156)	(9.680)	(6.420)	(8.407)	(9.459)	(11.94)	(5.980)	(6.694)	(10.19)	(9.739)
Observations	1,256	1,254	1,249	1,169	1,205	1,189	1,197	1,192	1,266	1,261	1,181	1,189	1,253	1,261	1,254	1,256
R-squared	0.716	0.581	0.490	0.419	0.724	0.554	0.501	0.409	0.744	0.588	0.486	0.447	0.577	0.531	0.442	0.401

Panel C: Services

	spring				fall				summer				winter			
Horizon	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3	0	+1	+2	+3
Temperature	-0.0680	-0.128	-0.241**	-0.244**	0.0859	0.00183	0.0393	0.0530	-0.0175	0.130	0.236	0.368***	0.00377	-0.0798	0.0242	0.0173
	(0.0913)	(0.0805)	(0.0958)	(0.112)	(0.0774)	(0.0907)	(0.0822)	(0.0932)	(0.103)	(0.133)	(0.144)	(0.128)	(0.0806)	(0.0714)	(0.0637)	(0.0674)
Temperature*extreme heat dummy	7.94e-05	0.00158	0.00412	0.0122	-0.00362	-0.0101	-0.0126	-0.00899	0.00517	-0.0141*	-0.0158*	-0.0246***	0.00501	0.000279	0.00679	0.0121
	(0.00658)	(0.00696)	(0.00691)	(0.00835)	(0.00797)	(0.00751)	(0.00934)	(0.0102)	(0.00654)	(0.00713)	(0.00911)	(0.00811)	(0.00746)	(0.00792)	(0.00900)	(0.0107)
Constant	0.847	0.477	1.928	4.528	3.870*	0.376	5.071	1.902	-1.265	-3.771	-4.741	2.643	3.495	5.934	2.354	3.688
	(2.924)	(3.872)	(4.681)	(5.966)	(2.260)	(4.118)	(4.151)	(4.954)	(2.933)	(3.291)	(5.265)	(4.692)	(4.005)	(3.594)	(4.137)	(4.448)
Observations	1,282	1,278	1,273	1,209	1,221	1,220	1,221	1,209	1,287	1,281	1,219	1,220	1,283	1,283	1,271	1,265
R-squared	0.740	0.686	0.616	0.531	0.740	0.639	0.595	0.522	0.786	0.670	0.571	0.560	0.652	0.625	0.568	0.531

Notes: The table presents the econometric results following equation (9). Robust standard errors in paratheses. * p<0.1, ** p<0.05, *** p<0.01

Annex I.

List of countries with quarterly value-added data.

Advanced countries (30)	**EMDEs (44)**
Australia, Belgium, Canada, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong SAR, Ireland, Israel, Italy, Korea, Latvia, Lithuania, Netherlands, New Zealand, Norway, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Taiwan Province of China, United Kingdom, United States	Albania, Argentina, Azerbaijan, Belarus, Bolivia, Brazil, Bulgaria, Chile, China, Colombia, Croatia, Ecuador, Georgia, Ghana, Guatemala, Hungary, India, Indonesia, Iran, Jordan, Kazakhstan, Kenya, Malaysia, Mexico, Morocco, Nigeria, North Macedonia, Panama, Paraguay, Philippines, Qatar, Romania, Russia, Saudi Arabia, Serbia, South Africa, Sri Lanka, Tanzania, Thailand, Tunisia, Turkey, Uganda, Ukraine, Vietnam

List of countries with quarterly GDP data.

Advanced countries (30)	**EMDEs (57)**
Australia, Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, Germany, Greece, Hong Kong SAR, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Netherlands, New Zealand, Norway, Singapore, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Taiwan Province of China, United Kingdom, United States	Albania, Argentina, Azerbaijan, Bahrain, Belarus, Bolivia, Brazil, Bulgaria, Chile, China, Colombia, Croatia, Egypt, Georgia, Ghana, Guatemala, Honduras, Hungary, India, Indonesia, Iran, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyz Republic, Lebanon, Malaysia, Mexico, Moldova, Montenegro, Rep. of, Nicaragua, Nigeria, North Macedonia, Panama, Paraguay, Peru, Philippines, Poland, Qatar, Romania, Russia, Rwanda, Saudi Arabia, Serbia, South Africa, Sri Lanka, Tanzania, Thailand, Turkey, Uganda, Ukraine, United Arab Emirates, Uzbekistan, Venezuela, Vietnam, Zambia

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