Seasonal temperature variability and economic cycles *

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Abstract

In this paper, I examine to what extent temperature variability can explain seasonal economic cycles. To this aim, I first construct a novel dataset of seasonal temperature and seasonal economic production for a sample of 98 countries. This dataset reveals a much larger diversity of seasonal economic cycles around the world than previously reported. I then attribute these economic cycles to variation in temperature. For identification, I propose and apply a novel econometric approach based on seasonal differences that accounts for expectations. The results suggest that seasonal temperature has a statistically significant positive effect on seasonal production. Using data on GVA for different industry groups I can attribute this effect to industries that are relatively more exposed to ambient temperature. Furthermore, the results suggest that economic development makes countries more resilient to temperature fluctuations. Overall, the effect of temperature on seasonal economic cycles appears large, as in many countries the effect of temperature is strong enough to explain almost all of the observed seasonal economic cycle. Regarding future anthropogenic climate change, the results suggest that changes to seasonal temperatures will lead to a reallocation of economic activity from one season to another of up to several percentage points of annual GDP, pointing to yet another channel through which climate change will affect economic production that has so far been overlooked.

Keywords: seasonal cycles, macroeconomic fluctuations, temperature variability

JEL codes: E32, E23, Q54

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1 Introduction

A large part of the variation of timeseries of macroeconomic variables is due to seasonality (Hylleberg et al., 1993). Understanding the causes of this seasonality has been an active area of macroeconomic research. While it has long been conjectured that some of the seasonality can be attributed to weather, research has come to the conclusion that observed quarterly variation of GDP can mostly be explained by recurring shifts in preferences and technologies due to high consumption around Christmas and mid-year vacations (Beaulieu et al., 1992; Barsky and Miron, 1989; Cubadda et al., 2002; Beaulieu and Miron, 1992; Braun, 1995; Chatterjee and Ravikumar, 1992; Miron and Beaulieu, 1996; Franses, 1996). Furthermore, it has been pointed out that an important role of temperature seems to be in contradiction with similar economic cycles observed in countries in different hemispheres experiencing opposite seasons (Beaulieu et al., 1992). However, these conclusions were based on small samples of mostly OECD countries and little attention was paid to causal identification and to attribution of observed fluctuations to fundamental rather than proximate drivers. Given that anthropogenic climate change is projected to change seasonal cycles of temperature (Dwyer et al., 2012), the role of temperature for fluctuations of GDP appears to be an important question.

In this study, I empirically examine and attempt to quantify the influence of temperature on seasonal economic cycles. To do so, I construct a new dataset covering the period 1990-2018 using a global dataset of quarterly Gross Domestic Product (GDP) covering 98 countries, a dataset on quarterly Gross Value Added (GVA) for 35 European economies, and climate reanalysis. Using information on quarterly temperature, I define seasons in a consistent way across countries in different hemispheres. To identify the effect of seasonal temperature on seasonal economic production, I propose and apply a novel econometric approach using variation across countries in terms of the differences in temperature and economic production between summer and winter.

Using this newly constructed dataset, I first identify stylised facts about quarterly fluctuations of GDP in countries around the world. Previous studies were based on fewer economies mostly located in the Northern hemisphere and reported relatively similar cycles across countries with a primary peak of production in the fourth quarter and a trough in the first quarter. In contrast to these results, I find a large diversity of quarterly economic cycles across countries. Of the 24 possible patterns, 21 are observed by at least one country in the sample. Economic cycles also seem to systematically differ between countries in the Northern and in the Southern hemisphere. Furthermore, after aggregating quarterly production to production in the summer half-year and winter half-year (months 4-9 and 10-3 respectively, to which I refer in the following as seasons), I find that production is larger in summer in 55 countries and larger in winter in 43 countries.

Examining the contribution of temperature to these cycles, I find that seasonal temperature has a statistically significant positive effect on seasonal production. This effect is primarily due to countries with larger production in summer than in winter. For the remaining countries, I find an insignificant but negative effect of temperature on production. I state the assumptions under which these effects can be interpreted as causal and find that the estimated effects are robust to inclusion of a variety of control variables, including annual mean temperature and the level of GDP per capita. Overall, the estimated effect of temperature appears large and in most countries can explain almost all of the observed seasonal differences in GDP. Using the GVA data for different industry groups for European economies, I find a statistically significant effect of seasonal temperature on GVA only for relatively temperature-exposed industries, consistent with an effect of temperature on the supply side of the economy.

This paper contributes to previous work on seasonal economic cycles (Beaulieu et al., 1992; Barsky and Miron, 1989; Cubadda et al., 2002; Beaulieu and Miron, 1992; Braun, 1995; Chatterjee and Ravikumar, 1992; Miron and Beaulieu, 1996; Franses, 1996; Lumsdaine and Prasad, 2003). While a possible role for temperature has frequently been acknowledged, these cycles have been explained primarily with recurrent shifts of preferences and technologies. These conclusions were reached based on small samples of mostly OECD countries. My results suggest that more attention should be paid to the large heterogeneity of seasonal economic cycles across countries. Furthermore, while preference and technology shocks might still explain a substantial share of the total variation of quarterly production and are also possible channels through which temperature affects production, I find that in many countries temperature alone can explain a large portion of the difference in economic production between summer and winter.

This paper also contributes to previous work on the effect of temperature on economic production. Previous work suggests a positive effect of annual mean temperature on economic production in relatively cold (and rich) and a negative effect in relatively warm (and poor) countries (Dell et al., 2012; Burke et al., 2015; Kalkuhl and Wenz, 2020). In this paper, I find evidence for an overall positive effect of seasonal temperature on seasonal production in countries with larger production in summer than in winter, but I also explain how this estimated effect is conceptually different from the estimated effect of annual temperature on annual GDP estimated in previous studies. Regarding future anthropogenic climate change, my results suggest that changes to the seasonal temperature cycle will cause a reallocation of economic activity across seasons. Using projections of climate models, I find that this reallocation can be substantial, up to several percentage points of annual GDP.

The paper is structured as follows. In the next Section, I present the theoretical framework, explain the identification strategy, and describe the data used in this study. In Section 3, I first present stylised facts of seasonal economic cycles for my global sample of 98 countries. I then discuss results obtained from my econometric estimation, before showing stylised facts and econometric results for the data on industry groups for 35 countries in Europe. Furthermore, I combine my empirical estimates with results from climate models to quantify the order of magnitude of future possible seasonal reallocation of economic production. In Section 4, I discuss my results in more detail regarding previous findings on the costs of anthropogenic climate change. Conclusions are drawn in Section 5.

2 Methods

2.1 Theoretical framework

Identifying the causal effect of temperature on economic production requires an empirical framework that takes into account expectations. This is especially important for seasonal changes of temperature which are recurring every year and thus likely to be anticipated. In essence, seasonal cycles of temperature can be considered as a characteristic of the climate of a location, rather than its weather. To illustrate the challenge of causal identification in the presence of expectations and to explain the solution proposed in this paper, I start by formulating a simple conceptual model of economic production Y as a function of climate $\mathbf{C}$ and other factors $\mathbf{X}$. I follow Hsiang (2016) and assume that climate influences production through two channels: through the actually realised weather $\mathbf{c}$ and through beliefs about climate $\mathbf{b}$:

$$Y(\mathbf{C}, \mathbf{X}) = Y[\mathbf{c}(\mathbf{C}), \mathbf{b}(\mathbf{C}), \mathbf{X}] \tag{1}$$

In this framework, both climate $\mathbf{C}$ and weather $\mathbf{c}$ are charaterised by meteorological variables that describe the state of the atmosphere, such as temperature, precipitation, and humidity. The difference between the two concepts is that climate $\mathbf{C}$ refers to the (theoretical) probability distribution of these variables, while weather $\mathbf{c}$ refers to the (empirical) frequency distribution of their actually realised values. In other words, climate refers to the population of possible events, whereas weather refers to a sample drawn from that population. Weather can affect economic production directly for example through effects of precipitation on agricultural output or effects of temperature on the productivity of labour. Beliefs $\mathbf{b}$ are based on climate and affect economic production through actions of economic agents that are influenced by the expected future weather, such as the choice of production technology.

Climate and weather are specific to a location and a specific time period. Climate is typically defined for a period of 30 years, whereas weather is defined for shorter periods (hours, days, maybe a year). The term climate is commonly also used to refer to the statistics of weather of only certain parts of a year. For the purpose of this paper I use the term *seasonal climate* to refer to the climate of specific months. For example, seasonal climate can refer to the average weather of the months January, February, and March in London over the time period 1981-2010.

Given Equation 1 the marginal effect of (seasonal) climate on production can be written as

$$\frac{\partial Y(\mathbf{C})}{\partial \mathbf{C}} = \sum_{k=1}^{K} \frac{\partial Y(\mathbf{C})}{\partial \mathbf{c}_k} \frac{\mathrm{d}\mathbf{c}_k}{\mathrm{d}\mathbf{C}} + \sum_{n=1}^{N} \frac{\partial Y(\mathbf{C})}{\partial \mathbf{b}_n} \frac{\mathrm{d}\mathbf{b}_n}{\mathrm{d}\mathbf{C}} \tag{2}$$

The (marginal) effect of climate on production can hence be considered as the sum of direct effects (first term of Equation 2) and belief effects (the second term of Equation 2). For simplicity, it is assumed here that agents form their beliefs based on only climate and not weather.

2.2 Identification strategy

The decomposition of the marginal effect of climate on economic production into two channels has implications for its identification in empirical research. This identification can generally be based on variation across time or across units of observation. Depending on this choice, the two channels in Equation 2 will be captured to a greater or lesser extent by empirical estimates. Generally, variation of output across units of observations includes both direct and belief effects of climate, but cross-sectional estimates are prone to omitted variable biases. Exploiting variation of temperature and output over time at a frequency of days, months, or years removes possible biases of unobserved time-invariant effects, but is unlikely to recover belief effects of climate.

This trade-off between a plausible identification of causal effects of climate and the credible identification of both direct and beliefs effects of climate is a thread throughout the climate econometrics literature (Hsiang, 2016). For the purpose of this paper, I propose a new empirical strategy for navigating this trade-off. The strategy relies on temperature differences between two seasons of the same year. It can be considered a hybrid approach, exploiting variation across time and across units of observations for identification. In this respect, it resembles the long-differences approach of panel data analysis (Hsiang, 2016). In mathematical terms, I propose to estimate an Equation:

$$Y_{i\tau_1} - Y_{i\tau_2} = \alpha + (\mathbf{c}_{i\tau_1} - \mathbf{c}_{i\tau_2})\beta + (\mathbf{x}_{i\tau_1} - \mathbf{x}_{i\tau_2})\gamma + \tilde{\mathbf{x}}_i\delta + \epsilon_i \tag{3}$$

where seasonal weather over a time period of several years is indxed by τ_1 and τ_2, with a vector of time-varying controls $\mathbf{x}$, and with a vector of time-invariant controls $\tilde{\mathbf{x}}$. The two seasons can be considered as any two time periods within a year for which both temperature and production are observed. In the empirical part of the paper, I distinguish two seasons summer and winter and use two alternative ways of assigning the four quarters of a year to these two seasons (Section 2.3).

Identification of a causal effect of seasonal climate using Equation 3 relies on a special form of the *unit homogeneity assumption*:

$$\mathrm{E}[Y_{i\tau_1} - Y_{i\tau_2}|\mathbf{c}_{\tau_1} - \mathbf{c}_{\tau_2}, \mathbf{x}_{i\tau_1} - \mathbf{x}_{i\tau_2}, \tilde{\mathbf{x}}_{\mathbf{i}}] = \mathrm{E}[Y_{j\tau_1} - Y_{j\tau_2}|\mathbf{c}_{\tau_1} - \mathbf{c}_{\tau_2}, \mathbf{x}_{j\tau_1} - \mathbf{x}_{j\tau_2}, \tilde{\mathbf{x}}_{\mathbf{j}}] \tag{4}$$

or, using the greek letter Δ to denote seasonal differences,

$$\mathrm{E}[\Delta Y_i|\Delta\mathbf{c}, \Delta\mathbf{x}_i, \tilde{\mathbf{x}}_{\mathbf{i}}] = \mathrm{E}[\Delta Y_j|\Delta\mathbf{c}, \Delta\mathbf{x}_j, \tilde{\mathbf{x}}_{\mathbf{j}}] \tag{5}$$

This assumption differs from the unit homogeneity assumption of a conventional cross-sectional regression in that it does not require that the expected *levels* of production are the same for two units of observation conditional on the level of climate and on observables, but that expected *seasonal differences* of production are the same for two units of observation conditional on the same seasonal differences in climate and conditional on observables. This means that the effect of any time-invariant variables that affect production in both seasons in the same way, such as the level of education of the workforce, cannot confound the estimated relationship.

Furthermore, the identification of both direct and belief effects of differences in the seasonal climate on differences in economic production relies on a *treatment comparability assumption*

$$\mathrm{E}[Y_i|\mathbf{c}_{\boldsymbol{\tau_1}}] - \mathrm{E}[Y_i|\mathbf{c}_{\boldsymbol{\tau_2}}] = \mathrm{E}[Y_i|\mathbf{C}_{\boldsymbol{\tau_1}}] - \mathrm{E}[Y_i|\mathbf{C}_{\boldsymbol{\tau_2}}] \tag{6}$$

This assumption is more credibly satisfied the longer the time period used to characterise seasonal weather $\mathbf{c}$.

While seasonal-differences can be used to estimate the effect of any climate variable, the focus of this paper is on temperature. Temperature differences between summer and winter are primarily determined by the amplitude of the annual cycle of the intensity of the Sun's radiation at the surface and are thus larger at higher latitudes. Empirical work on the factors underlying seasonal economic cycles point to a preference shift around Christmas and a technology shifts around July and August due to vacations. Any unobserved variable that is correlated with the amplitude of both these cycles can confound the estimated relationship. In this paper, I use annual mean temperature as a control variable as it is also primarily determined by latitude. Furthermore, I use the share of the Christian population as a control variable as it might affect the magnitude of the consumption boom around Christmas. The amplitude of the seasonal economic cyles might also be affected by the structural composition of an economy as some sectors might be more exposed to technology and preference shifts or temperature than others. For this reason, I include the level of GDP per capita and the share of agricultural GDP as control variables. In additional robustness tests whose results are shown in the Appendix, I include a wide range of additional control variables related to sectoral shares, trade, tourism, interest rates, religion, and geography. Furthermore, in an analysis focusing on European economies, I also examine the effect of temperature on gross value added for 11 industry groups, which sheds further lights on the role of sectoral composition. Furthermore, the latter sample if generally more homogeneous and thus less likely to be affected by certain possible omitted variable biases.

The seasonal-differences approach proposed here resembles the long differences approach in that it can be considered a hybrid approach using variation over time and over space for identification (Hsiang, 2016). The interpretation of the obtained estimates is however different. The main advantage of the seasonal-difference estimator as compared to the long-differences estimator for this paper is that it allows one to identify the effects of beliefs about differences between summer and winter, rather than beliefs about long-term trends. A more detailed comparison of the different identification strategies is drawn in Section 4.

2.3 Data

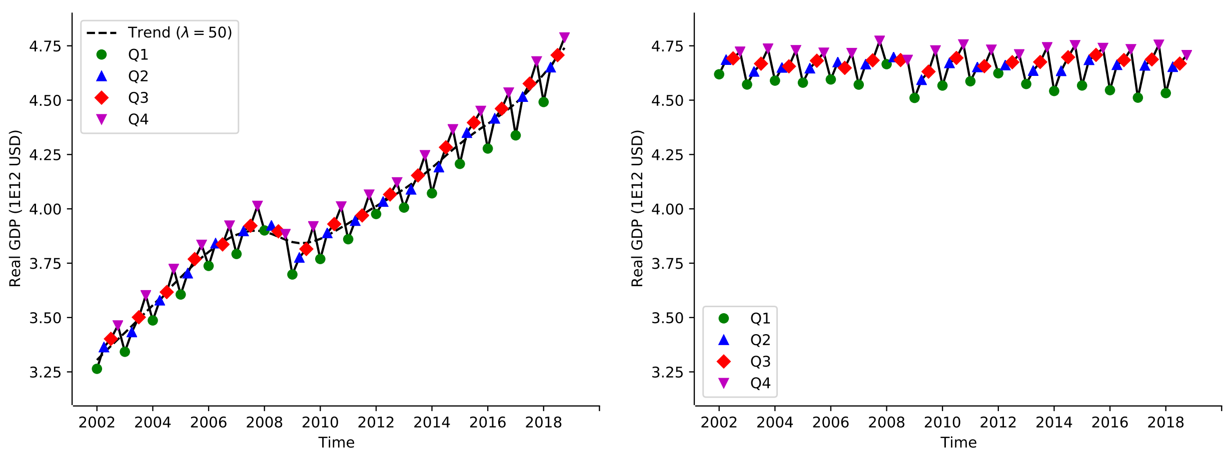
I use data on quarterly Gross Domestic Product (GDP) in USD provided by the International Monetary Fund (IMF). These inflation-adjusted data cover 98 countries with different temporal coverage across countries. The data include at least 5 years of observations for every country (the first year that data are available for Honduras is 2014 and for the Maldives 2012; for all other countries I have at least 8 years of data). In order to improve the balance of the panel data, I reduce the sample to the years 1990-2018 for all countries. In a robustness test whose results are shown in the Appendix I use only data over the period 2014-2018 for all countries and find very similar results. I combine this economic data with the climate reanalysis ERA5 provided by the European Center for Medium Range Weather

Forecast (ECMWF). I use monthly mean temperature levels and monthly mean daily precipitation which I aggregate to quarterly frequency. The data have a spatial resolution of 0.25 degrees (approximately 25 km at the Equator) which I aggregate to the level of countries using grid-cell population from the Gridded Population of the World (GPW) dataset as weights.

I also use data on quarterly Gross Value Added (GVA) for 11 industry groups provided by EUROSTAT. The data covers 35 countries in Europe. The data cover again different time periods across countries, with all countries reporting for at least 10 years (since 2009).

To identify seasonal patterns in the timeseries, I first detrend the data. I use a Hodrick-Prescott Filter with $\lambda = 50$. After removing the deterministic trend, I add the mean value of the last year in the timeseries. The process is illustrated for timeseries of the USA in Figure 1.

Figure 1. Timeseries of quarterly real production for the USA before (left) and after detrending (right).



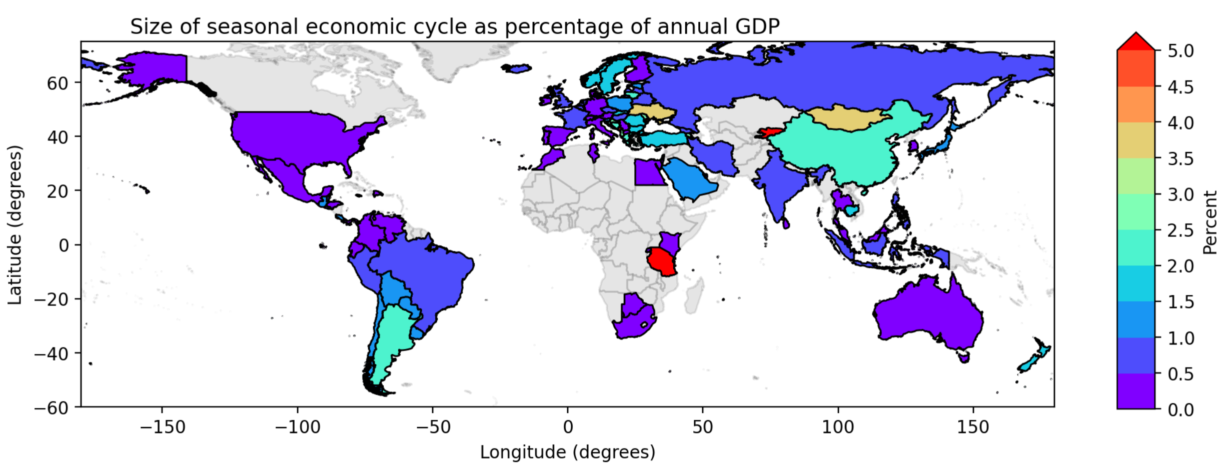
The identification strategy requires to define two seasons consistently across locations. The seasonal cycle of temperature is due to the tilt of the Earth's rotation axis and driven by the movement of the Earth around the Sun. From an Earth-centric perspective, the seasonal cycle of temperature arises from a perpetual oscillation between the time period with the maximum and the time period with the minimum of the amount of Solar radiation received at the top of the atmosphere. Except for locations close to the Equator, where variation in the distance between Earth and Sun dominates the oscillation of received Solar radiation, the time periods of minimum and maximum irradiation are around mid of December and mid of June respectively in the Northern hemisphere. In the Souther hemisphere, the pattern is the opposite.

For data with quarterly frequency a natural choice is thus to aggregate quarterly data to two time periods summer and winter. For a country in the Northern hemisphere the quarters 2 and 3 (months 4-9) can generally be considered as summer (τ_j, $j \in \{1, 2\}$) and the quarters 1 and 4 (months 1-3 and 10-12, respectively) as winter (τ_{3-j}). For countries not too close to the Equator, winter and summer defined this way will result in warmer and colder six months periods, respectively. Countries close to the Equator can experience more complex seasonal cycles with several peaks and troughs over the course of a year. For the empirical part of the paper I thus aggregate the four quarters to two seasons and then categorise the two six months periods as summer (S) and winter (W) for every country based on their average temperature. This ensures that the period referred to as summer is everywhere the warmer of the two six months periods of the year. I then use this assignment of the four quarters of a year to summer and winter to sum the detrended quarterly GDP for every country to seasonal GDP, that is GDP in summer and GDP in winter (illustrated for the USA and Brazil in Figure A1 in the Appendix).

This assignment of quarters to two seasons has the advantage that economic production of all four quarters is taken into account. An alternative choice is considering the warmest quarter as summer and the coldest quarter as winter. Results obtained with this definition of seasons are shown in the Appendix.

The magnitude of the seasonal cycle, defined as the difference between GDP in summer and winter divided by the annual GDP, is shown in Figure 2. The map reveals some geographical heterogeneity but no apparent pattern associated with latitude.

Figure 2. Size of the seasonal economic cycle (difference between production in the summer half-year and in the winter half-year) as percentage of annual GDP.



For control variables I use several sources. Data on GDP per capita, land area, and the share of agriculture and manufacturing are taken from the World Development Indicator database of the World Bank. For data on trade, tourism, and interest rate I use the TC360 database of the World Bank. Information on religion is obtained from the Pew Research Center.

Projections of future climate change are taken from the CMIP6 ensemble as provided by the ECMWF. The model MPI-ESM1.2 is chosen as previous studies have shown relatively small biases for historical seasonal temperatures (Xu et al., 2021). Results for Europe also suggest that future warming of seasonal mean temperatures is robust across the model ensemble (Carvalho et al., 2021). I download monthly mean values for the historical period 1990-2014 and for the future periods 2041-2070 and 2071-2100. The monthly means are then used to calculate seasonal means. The seasons are defined as for the empirical analysis described above.

The analysis of future projections is based on future changes instead of future absolute values. This has the advantage that no bias correction is required, as future changes are calculated from simulations of past and future climate with the same climate model. This approach is also referred to as the delta method and very common in climate impact research. To calculate future changes I first compute mean values for both periods, 2041-2070 and 2071-2100, and then subtract the mean value of the historical period 1990-2014. All variables are aggregated from grid cells to the country level using the same population weights as for the ERA5 reanalysis data.

Descriptive statistics are shown in Table 1.

Table 1. Descriptive statistics.

Variable	Unit	Mean	Std.	Min.	Max.	No. obs.
Seasonal diff. in log GDP	USD 2010	-0.01	0.04	-0.22	0.12	98
Seasonal diff. in temperature Δ T	deg. C	-8.20	5.39	-24.09	-0.03	98
Seasonal diff. in precipitation Δ P	mm day-1	-0.03	0.06	-0.19	0.09	98
Annual mean temperature	deg. C	16.30	7.19	-0.48	28.02	98
Change in Δ T for RCP4.5, 2041-2070	deg. C	0.05	0.32	-0.98	0.69	98
Change in Δ T for RCP4.5, 2071-2100	deg. C	0.07	0.34	-0.78	0.91	98
Change in Δ T for RCP8.5, 2041-2070	deg. C	-0.07	0.36	-1.00	0.63	98
Change in Δ T for RCP8.5, 2071-2100	deg. C	-0.28	0.82	-2.25	1.30	98
Share of agriculture in GDP	percent	8.02	7.38	0.07	33.77	97
Share of manufacturing of GDP	percent	14.99	5.38	2.15	30.56	97
Share of exports of GDP	percent	44.48	30.03	10.27	187.10	98
Share of imports of GDP	percent	46.77	26.93	11.67	165.59	98
Share of tourism receipts of GDP	percent	14.41	15.07	1.91	84.67	98
Share of tourism expenditures of GDP	percent	6.54	3.22	2.21	19.85	98
Real interest rate	percent	6.47	6.97	-21.13	41.14	92
Share of Christian population	percent	58.24	35.20	0.04	99.44	98
Share of Muslim population	percent	18.49	31.28	0.01	99.95	98
log GDP per capita	USD 2010	9.63	0.92	7.06	11.65	98
Land area	1E6 km2	11.61	2.44	3.39	16.61	98
Latitude	degrees	25.97	26.36	-41.00	65.00	98

Notes: Seasonal differences calculated as winter (W) minus summer (S).

3 Results

3.1 Stylised facts on seasonal economic cycles

Research over the last 35 years has mostly come to the conclusion that recurring shifts in preferences and technologies can explain most of the seasonal variation of economic activity (Beaulieu et al., 1992; Barsky and Miron, 1989; Cubadda et al., 2002; Beaulieu and Miron, 1992; Braun, 1995; Chatterjee and Ravikumar, 1992; Miron and Beaulieu, 1996; Franses, 1996). These shifts have been explained especially with high consumption during Christmas and vacations in June, July and August, leading to potentially very similar seasonal economic cycles across countries and industries. These conclusions were however based on small samples of countries, exclusively developed economies and mostly located in the Northern hemisphere.

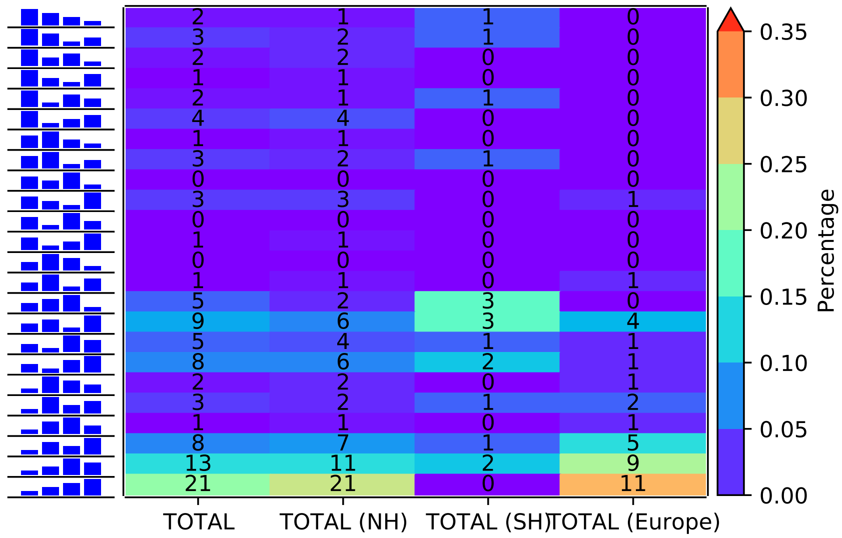
I thus first identify stylised facts about seasonal cycles in my sample of 98 economies. For every country I first regress trend-adjusted quarterly production on quarterly dummy variables. I then use the estimated coefficients of the four dummy variables to identify the pattern of the seasonal cycle. I distinguish 24 possible patterns. For example, the first of the 24 patterns corresponds to production tending to be largest in the first quarter, followed by the second, third, and fourth quarter.

Furthermore, to account for oppposite seasonal cycles of temperature, I split the sample into countries located in the Northern hemisphere (NH) and countries in the Southern hemisphere (SH). To do so, I compare the average temperature of the months 10-12 and 1-3 with the average temperature of the months 4-9. A country is then assigned to the Northern Hemisphere if the months 4-9 are warmer than the months 10-12 and 1-3.

Overall, seasonal economic cycles around the world appear quite diverse, with 21 of the 24 possible patterns being exhibited by at least one country. The most common pattern in the sample (21 of 98 countries) is a peak of production in the fourth quarter, followed by the third, second, and first quarter (Figure 3). The second most frequent pattern (13 of 98) is a peak in the third quarter, followed by the fourth, second, and first quarter. Pointing again to systematic differences between the two hemispheres, the most frequent pattern in the Northern hemisphere is not shown by any country in the Southern hemisphere.

This new evidence on quarterly cycles also reveals that some stylised facts identified by previous work are not as widespread as that work might suggest. One of these facts is a peak of production in the fourth quarter, possibly due to consumption boom around Christmas (Beaulieu and Miron, 1992). I find that this is primarily a phenomenon of countries in the Northern hemisphere and can be found only in about half of those countries (Figure 3). In the full sample, 49% of countries (48 out of 98 countries) have the maximum production in

Figure 3. Frequency of patterns of quarterly economic production.



Notes: Columns correspond to different samples: full sample, countries in the Northern hemisphere, countries in the Southern hemisphere, and countries in Europe. Colors indicate relative frequency based on size of corresponding sample.

the fourth quarter. These represent 54% of countries (44 of 81 countries) in the Northern hemisphere and 24% of countries (4 of 17 countries) in the Southern hemisphere.

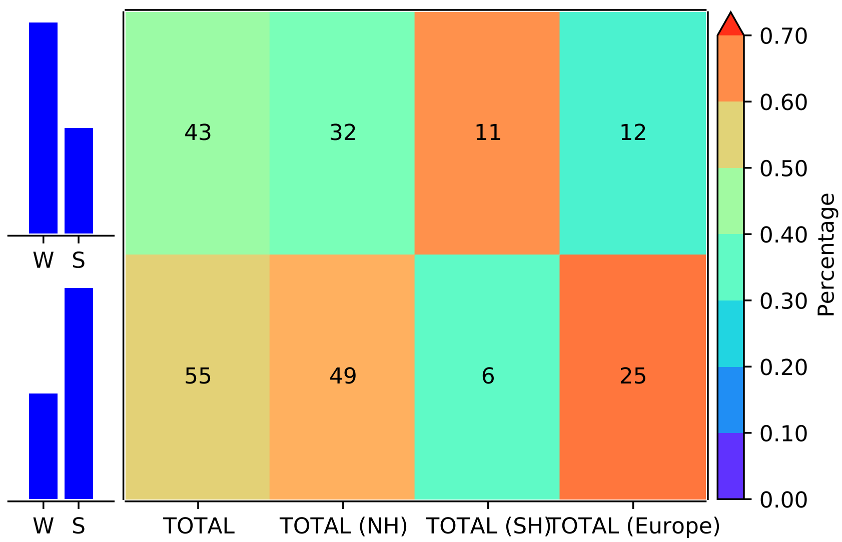
Another stylised fact reported previously is a trough of production in the first quarter of the year, possibly due to reorganisation of production and generally economic activities at the beginning of the calendar year that result in less measurable economic output. Again I find that this can be found in countries in the Northern hemisphere (54%, or 44 countries) more frequently than among countries in the Southern hemisphere (35%, or 6 countries), but also that this fact is even in the Northern hemisphere only exhibited by about half of all countries.

A third stylised fact reported previously is a slowdown of economic activity around June, July, and August, possibly due to school holidays in many countries and mid-year vacations. Such a local minimum of production in either the second or the third quarter can be found in 52% of countries (42 countries) in the Northern hemisphere (18 and 24 countries with a local minimum in the second and third quarter, respectively) and in 65% (11 countries) in the Southern hemisphere (4 and 7 countries, respectively).

In sum, all three stylised facts about seasonal economic cycles seem to be found in only about half of all countries. Furthermore, two of these facts seem to be primarily observed in the Northern hemisphere. One of these two, the peak of economic production in the fourth quarter, has been used to question the influence of temperature on seasonal economic cycles as countries in both hemispheres appeared to exhibit this feature in small earlier samples (Beaulieu and Miron, 1992). In contrast, the evidence of my larger sample suggests substantial differences between countries in the two hemispheres.

To reduce the dimensionality of the analysis and prepare the data for a model estimation based on seasonal differences, I next sum trend-adjusted production of the quarters 1 and 4 and 2 and 3 to semi-annual production. Based on the assignment of countries to the SH or NH, I refer to the quarters 1 and 4 as winter (summer) and to the quarters 2 and 3 as summer (winter) respectively. I refer to countries with larger production in summer as summer-peak countries and to all other countries as winter-peak countries.

Figure 4. Frequency of patterns of economic production in summer and winter.



Notes: Columns correspond to different samples: full sample, countries in the Northern hemisphere, countries in the Southern hemisphere, and countries in Europe. Colors indicate relative frequency based on size of corresponding sample.

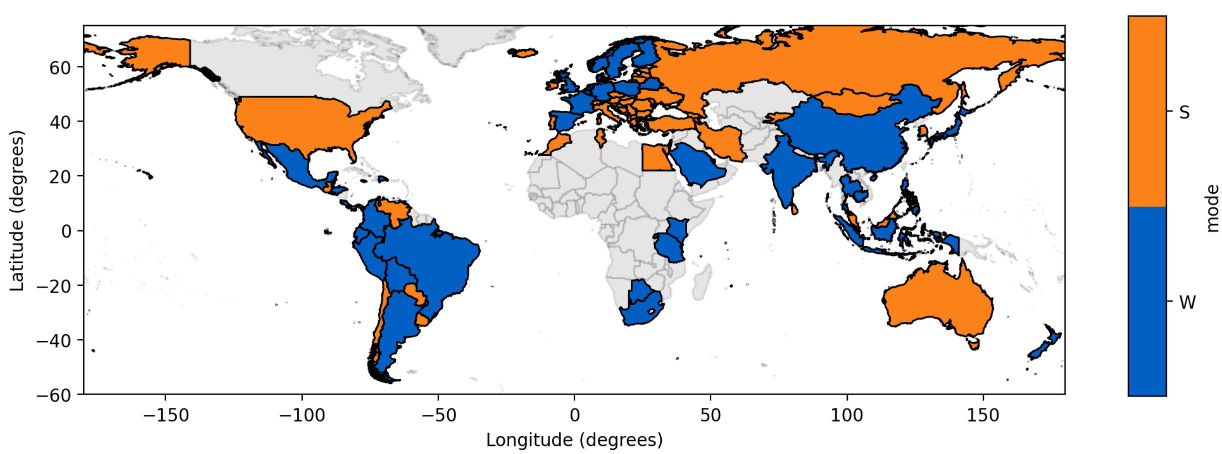
In the full sample, summer-peak countries are slightly more frequent than winter-peak countries (55%, or 55 of 98 countries) (Figure 4). In the Northern hemisphere, the share of winter-peak countries is slightly larger (60%, or 49 of 81 countries). In the Southern hemisphere, countries tend to have larger production in winter than in summer (65%, or 11 of 17 countries).

Relating these findings to the cycles at quarterly frequency, in the Northern hemisphere the smaller production in winter than in summer can partly be explained with the small production in the first quarter, which seems to dominate the large production in the fourth quarter and the small production in the third or second quarter. In the Southern hemisphere, the relatively small production in summer is in line with only few countries exhibiting a peak in the fourth quarter and most countries exhibiting a local minimum of production in the second or third quarter.

Overall, countries in the Northern hemisphere thus tend to have larger production in winter than in summer. The fact that production in winter tends to be the sum of the quarter with the maximum production and the quarter with the minimum production suggests to examine the effect of temperature not only at semi-annual but also at quarterly frequency.

The geographical distribution of summer-peak and winter-peak countries suggests some geographical clustering (Figure 5). For example, most countries in Northern and Western Europe are winter-peak countries, while most countries in Eastern Europe and the Middle East are summer-peak countries. In the Southern hemisphere, winter-peak countries (11 of 17) are more common than summer-peak countries. There is however no clear effect of absolute latitude, with winter-peak countries being relatively frequent at relatively high and at low latitudes.

Figure 5. Geographical distribution of winter-peak (W) and summer-peak (S) countries.



I examine the balance of the two subsamples also more formally using statistical tests (Table A1 in the Appendix). I find that winter-peak countries tend to have a smaller (less positive) temperature difference between summer and winter ($p < 0.001$) and a more negative difference in rainfall (relatively more rainfall in summer than in winter) ($p < 0.01$). Furthermore, they tend to have a higher annual mean temperature ($p < 0.05$), to be located closer to the South Pole and closer to the Equator ($p < 0.05$). I quantify the contribution of different factors to the observed patterns, including the role of temperature, in the next

Section.

3.2 The contribution of seasonal temperature variability

In order to examine the contribution of temperature to seasonal economic cycles, I estimate my seasonal difference model (Equation 3) using the data on 98 countries illustrated in the previous section. I find a significant positive effect of temperature on production (Column 1 in Table 2). The effect is robust to including a variety of control variables including annual mean temperature and GDP per capita level (Column 2). The results are also robust to including a large number of additional control variables (Table A2 in the Appendix), to using only data from the years 2014-2018 (Table A3 in the Appendix), and to using the differences between the quarters with maximum and minimum temperature (Table A5). As expected, using differences between six-months periods instead of quarters of which in many countries one six-month period is composed of the quarter with the maximum and the quarter with the minimum production attenuates the estimated effect of temperature (Table A5). Including interaction terms in the model, I find that the effect of temperature is smaller in countries with higher level of GDP capita (Column 3).

The size of the effect of temperature is economically large. The sample mean of the difference in seasonal temperatures of about 8.2 degree Celsius (Table 1) is associated with a difference in seasonal GDP of about 2.4 percent. This effect is of the same order of magnitude as the mean difference in seasonal GDP (Table 1). The effect seems not to be driven by outliers and there is no apparent difference in the magnitude of the effect between countries on the Northern and on the Southern hemisphere (Figure A2 in the Appendix).

This suggests that temperature is an important factor contributing to the larger production in summer than in winter that is observed in many countries (Figure 5). This raises the question whether those countries with production larger in winter than in summer are different in terms of how their production is affected by temperature or whether temperature has a similar effect but in those countries other factors, such as seasonal preference and technology shifts that are unrelated to weather, are relatively more important. To address this question, I split the full sample based on whether a country has larger production in summer or in winter (Figure 5) and estimate the same models for the two subsamples. I refer to countries in these subsamples in the following as summer-peak and winter-peak countries respectively.

The estimated effects of temperature on production for summer-peak countries are very similar to the effects estimated for the full sample, but for winter-peak countries the estimated effect of temperature has the opposite sign (Column 4 in Table 2). These results suggest that countries have different sensitivities to temperature with potentially opposite signs. For

Table 2. Results of regressions using a global sample of GDP of 98 countries.

Dependent variable:	Δ *log GDP*				
Sample:	All countries			S	W
Column:	1	2	3	4	5
ΔT	0.0029***	0.0031***	0.0231***	0.0212**	-0.0094
	(0.0006)	(0.0008)	(0.0064)	(0.0096)	(0.0078)
Annual mean temperature $\cdot \Delta T$			0.0000	0.0000	0.0002
			(0.0001)	(0.0001)	(0.0001)
log GDP pc $\cdot \Delta T$			-0.0022***	-0.0021**	0.0006
			(0.0007)	(0.0010)	(0.0009)
Annual mean temperature		0.0003	0.0007	0.0011	0.0018
		(0.0006)	(0.0008)	(0.0011)	(0.0013)
log GDP pc		0.0068	-0.0129	-0.0157*	0.0013
		(0.0058)	(0.0089)	(0.0089)	(0.0121)
Share of agriculture of GDP		-0.0008	-0.0012*	-0.0014	-0.0002
		(0.0009)	(0.0007)	(0.0011)	(0.0011)
Share of Christian population		-0.0139	-0.0191**	-0.0104	-0.0080
		(0.0096)	(0.0090)	(0.0095)	(0.0120)
log Landarea		0.0046***	0.0040**	0.0037*	-0.0001
		(0.0016)	(0.0016)	(0.0021)	(0.0013)
Intercept		-0.0916	0.0953	0.0986	-0.0288
		(0.0716)	(0.0966)	(0.1053)	(0.1271)
R2	0.17	0.31	0.38	0.36	0.22
R2 adj.	0.16	0.26	0.32	0.25	0.02
N	98	96	96	55	41

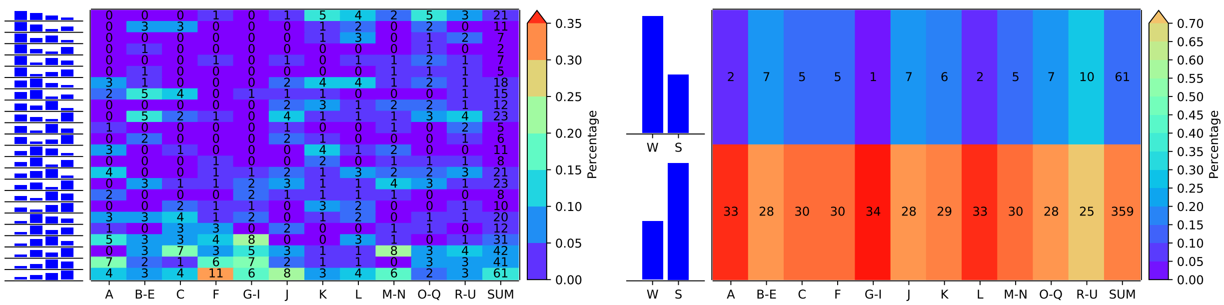
Notes: Seasonal differences Δ calculated as winter minus summer. Sample S = countries with peak of production in summer, W = countries with peak of production in winter. Significance as follows: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

some (summer-peak) countries temperature has a positive effect on economic production, these countries tend to have larger production in summer than in winter, and they also tend to allocate production increasingly from winter to summer the larger the temperature difference between the two seasons. At the same time, for some (winter-peak) countries temperature seems to have a negative effect on economic production and this is reflected in their seasonal production with larger production in winter than in summer. Furthermore, for winter-peak countries, the effect of temperature on production has a larger signal than for summer-peak countries but there also appears to be more variation among countries that cannot be explained with levels of GDP.

3.3 Effects by industry groups for European economies

The results in the previous section suggest that temperature has a positive effect on production in some countries and a negative effect in others. In this section, I explore to what extent this finding can be explained by differences in sectoral composition. To this aim, I use data on gross value added (GVA) by industry group for 35 countries in Europe. Focusing on Europe has the advantage that reporting quality is probably more homogeneous across countries than for the global sample and that also the climate and especially seasonal temperature cycles are more similar. Furthermore, EUROSTAT provides to my knowledge the most comprehensive homogeneous database of quarterly production by industry group.

Figure 6. Frequency of patterns of quarterly GVA (left) and winter and summer GVA (right) for different industry groups for a sample of 35 European economies.



Notes: Columns correspond to different industry groups. Colors indicate relative frequency. Industry groups as follows: A: Agriculture, forestry and fishing, B-E: Industry (except construction), C: Manufacturing, F: Construction, G-I: Wholesale and retail trade, transport, accommo., J: Information and communication, K: Financial and insurance activities, L: Real estate activities, M-N: Professional, scientific and technical activit., O-Q: Public administration, defence, education, hum., R-U: Arts, entertainment and recreation; other serv.

I first explore the stylised facts as reported for total production and a global sample above. The most frequent pattern of the global sample of GDP was a peak of production in the fourth quarter, followed by the third, second, and first quarter. I find that this pattern can also be observed in every industry group for at least some countries (Figure 6). In 3 of the 11 industry groups, it is indeed the most frequent pattern, as well as if observations are summed across industry groups. However, Figure 6 also points to quite some diversity across industry groups and countries and every pattern appears at least for one country and one industry group.

Regarding the differences between summer and winter, the pattern is similar to the pattern for total GDP for countries in the Northern hemisphere. Specifically, production tends to be larger in summer than in winter in all industry groups (Figure 6). The distribution is most unequal for Wholesale and retail trade, transport, and accommodation (G-I) with 97% of countries (34 of 35 countries) exhibiting larger production in summer than in winter and most equal for Arts, Entertainment, and Recreation (R-U) with 71% of countries (25 of 35 countries).

Table 3. Results of regressions using a sample of GVA by industry groups of 35 European economies.

Dependent variable:	Δ *log GDP*		
Industries:	All	Exposed	Non-Exposed
Column:	1	2	3
ΔT	0.0033**	0.0054*	0.0019
	(0.0015)	(0.0027)	(0.0013)
Annual mean temperature	-0.0024**	-0.0014	-0.0021**
	(0.0011)	(0.0023)	(0.0008)
log GDP pc	0.0194*	0.0287	0.0176*
	(0.0097)	(0.0178)	(0.0091)
Share of agriculture of GDP	0.0000	-0.0012	0.0015
	(0.0011)	(0.0016)	(0.0009)
Share of Christian population	-0.0027	0.0246	-0.0217*
	(0.0151)	(0.0252)	(0.0126)
log Landarea	0.0048***	0.0073**	0.0036***
	(0.0016)	(0.0029)	(0.0012)
Intercept	-0.1971*	-0.3210	-0.1723*
	(0.1096)	(0.2083)	(0.0986)
R2	0.55	0.51	0.42
R2 adj.	0.45	0.41	0.29
N	35	35	35

Notes: Seasonal differences Δ calculated as winter minus summer. Exposed industries: Agriculture, Construction, Manufacturing, Utilities and Mining. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

To identify the effect of temperature on production, I next estimate the seasonal differences model in Equation 3 for each of the industry groups. I follow previous literature and group industries according to whether labour is relatively more or less exposed to outdoor temperature (Behrer and Park, 2019; Acevedo et al., 2020). I accordingly classify agriculture, construction, manufacturing, and mining and utilities as relatively exposed. I find a significantly positive effect of seasonal temperature differences on seasonal differences in GVA for total GVA and for GVA in exposed industries. For all other, non-exposed industries I find an insigificantly positive effect (Table 3). I conduct the same exercise at the level individual industries and find significantly positive coefficients for Construction and Mining and Utilities (Table A4 in the Appendix).

Robustness tests with the global sample of countries show that the estimated effect of temperature on economic production is unaffected by the inclusion of a variety of control variables including trade, tourism, and religion (Table A2 in the Appendix). This robustness suggests that other mechanisms are primarily responsible for the estimated effect. The results on GVA by industry groups suggest that exposure to ambient temperature moderates at least some of the effect, pointing to direct effects of temperature on productivity as a possible mechanism.

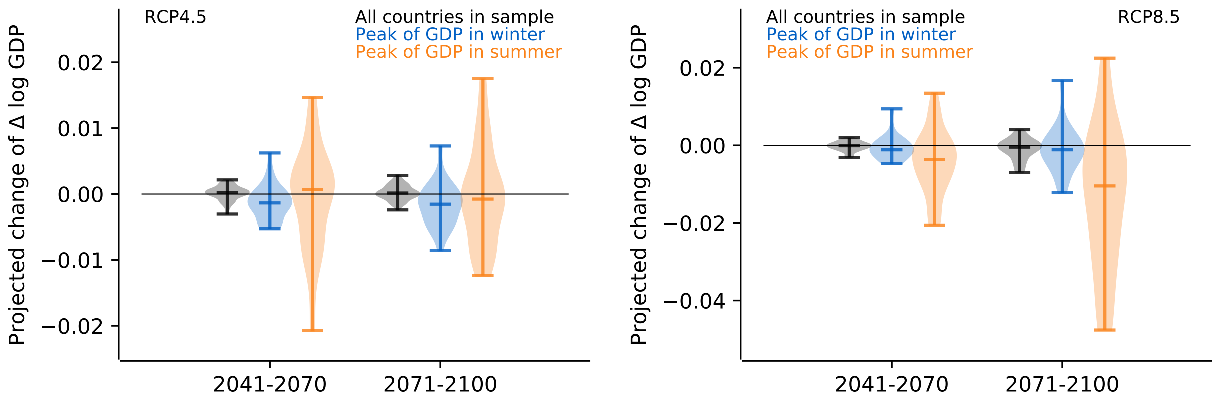
3.4 Scenarios of future climate change

These results suggest that economic production will be reallocated between winter and summer if under future climate change one season warms more quickly than the other. Such changes are indeed projected by global climate models. In a few countries, winters are projected to warm more quickly than summers because of reductions in snow cover in winter and accelerated warming due to the snow-albedo feedback (Carvalho et al., 2021). In most other countries outside the tropics, summers are projected to warm more quickly than winters because of increased dryness in summer and thus less humidity to moderate the projected warming (Byrne, 2021). The following analysis aims to quantify the approximate order of magnitude of possible reallocations of economic acitivity across the seasons due to these changes.

To this aim, I first combine climate model projections with the average empirically estimated effect of seasonal differences in temperature on seasonal economic production. I find that for about half of all countries, production will shift towards summer and for the other half towards winter (Figure 7). This is for the nearer (2041-2070) and the further away future (2071-2100), and for RCP4.5 and RCP8.5 scenarios. The magnitude of the effect by 2071-2100 is up to about 0.15 percentage points of annual GDP under RCP4.5 and up to 0.35 percentage points under RCP8.5.

These average estimates hide heterogeneity in the sample of countries. If I distinguish between countries with the peak of production in summer and those with the peak in winter, I find much larger effects (Figure 7). For both groups of countries, both time periods (2041-2070 and 2071-2100), and both scenarios (RCP4.5 and RCP8.5), production will tend to shift towards summer for the majority of countries. At the same time, other countries are expected to see similarly large shifts towards winter. The projected realloction of production is generally larger for summer-peak countries, reflecting a larger estimated coefficient (Table 2) and larger projected changes in temperature (Figure A3 and A4 in the Appendix).

Figure 7. Projections of Δ GDP for alternative scenarios of future climate change for the 98 countries in the sample.



Notes: The plot shows the distribution of the projected changes of Δ log GDP for individual countries in the vertical direction (violinplots). Horizontal bars indicate the maximum, mean, and minimum values. Seasonal differences Δ calculated as winter minus summer. Positive values mean that for the given scenario GDP will be reallocated from summer to winter.

The size of the projected seasonal reallocation of economic production is substantial. In winter peak countries, up to 0.8 percent of annual GDP is projected to be reallocated, while in summer peak countries this number is up to 2.4 percent (Figure 7). Mitigating climate change can substantially reduce this projected reallocation. By the end of the century, the projected reallocation for RCP4.5 is only about a fourth of its value for RCP8.5.

4 Discussion

The quarterly GDP data used in this paper cover 98 countries around the world representing all continents and a large range of socioeconomic contexts and climates. The analysis of heterogeneity suggests that the effect of seasonal temperature on seasonal GDP decreases with the level of GDP per capita of a country, but this pattern is based on relatively few economies in Africa, demanding caution when extrapolating from the global sample to other countries.

To identify the effect of temperature on economic production at seasonal frequency, a new identification strategy is proposed and applied. This seasonal-differences approach resembles the long differences approach in that it can be considered a hybrid approach using variation over time and over space for identification (Hsiang, 2016). In terms of the requirement of data, the seasonal-differences approach requires observations at sub-annual frequency (e.g.

quarters or months) of at least the treatment and the outcome variable, but it does not require observations going as far back in time as the long-differences approach. Furthermore, the seasonal-differences approach benefits from a larger temperature treatment at least in countries at higher latitudes for which temperature differences between summer and winter exceed gradual temperature trends by far (about one order of magnitude). At the same time the estimated effects require careful interpretation and are potentially less indicative for the effects of future changes to the climate of one season or to the annual climate than the results of a long-difference estimation. Furthermore, seasonal-differences estimates cannot be biased due to confounding long-term trends of unobservables that might affect long-difference estimations. However, the unit homogeneity assumption can still be violated due to an omitted variable that is correlated with seasonal differences in climate and in production.

The seasonal differences estimator relies on cross-sectional variation for identification. If Equations 5 and 6 are satisfied, the estimated parameter β can be interpreted as the causal effect of seasonal differences in climate on seasonal differences in economic production. However, there are two important caveats of this estimation approach. First, one must be careful about out-of-sample predictions. In this regard, in contrast to an estimation based on annual climate every unit (country) must be considered as a pair of seasonal observations. To illustrate, consider a country with an average summer temperature of 20 degrees C and an average winter temperature of 10 degrees C and assume that climate is fully characterised by the average seasonal temperature. In general, the difference in seasonal production should increase by the same amount in a scenario in which temperatures increase by 5 degrees C in summer as in a scenario with a similar decrease of temperature in winter. However, the sample of countries on which the estimation is based might not include both countries with 25 and 10 degrees and countries with 20 and 5 degrees C in summer and winter respectively. This limitation is especially important if temperature has a non-linear effect on economic activity, as some studies suggest (Burke et al., 2015; Kalkuhl and Wenz, 2020).

Second, one must be careful about using the estimated effect of seasonal differences to infer something about the effect of a change to the climate of only one season due to possible constraints on total economic production. Such constraints could be related to the supply side or the demand side of the economy. For example, production in construction might currently be larger in summer than in winter because of the more favourable weather, but it seems unlikely that production in winter would increase to the current level in summer if winter had the same temperature as summer because there might not be sufficient supply of labour or demand for construction services in the economy. Instead, a warmer winter is likely to lead to some redistribution of economic activity from summer to winter.

This second concern can be formalised as a likely violation of the *marginal treatment* *comparability assumption* (Hsiang, 2016)

$$\mathrm{E}[Y_i|\mathbf{c}_{\tau_1}] - \mathrm{E}[Y_i|\mathbf{c}_{\tau_2}] = \mathrm{E}[Y_i|\mathbf{C}_{\tau_1} + \Delta\mathbf{C}] - \mathrm{E}[Y_i|\mathbf{C}_{\tau_1}] \tag{7}$$

Relatedly, the estimated effects of seasonal differences is likely not the same as the effect of a change to the annual climate (a similar change to both seasons). This limitation is due to possible constraints mentioned in the previous paragraph and also due to certain possible costs and benefits of seasonality. Examples of the costs of seasonality are the costs of adjusting inputs to production. Adjusting inputs between seasons every year incurs these costs regularly, whereas adjusting inputs to a gradual change of temperature over many years incurs most likely lower or no such costs. The possibility of such costs suggests that the estimated effects of seasonal climate might be systematically smaller than the effects of annual climate. At the same time, seasonality might have certain benefits for production. For example, in the construction sector allocating most work to a few months of the year might reduce costs as compared to distributing the same amount of work across the year. The presence of such benefits suggests that effects of differences in seasonal climate might be systematically larger than the effects of a change to the annual climate.

These limitations concern the extrapolation of the estimated effects of differences in seasonal climate and inference about the marginal effect of a change to the climate of only one season or to the annual climate. The first limitation is important for the correct interpretation of the effects in this paper given the sample size of 98 countries. The second limitation is of minor concern as the focus is not on the consequences of future climate change, but on explaining the observed historical pattern. Regarding climate change, the estimated coefficients are most indicative of possible effects of changes to the seasonal cycle of temperature on the allocation of economic production between summer and winter.

5 Conclusions

This paper studies the effect of seasonal temperature on seasonal economic production. For causal identification I propose a novel econometric approach using variation of differences between seasons across countries. This seasonal-differences estimator is applied to a global sample of 98 countries using data from the IMF and climate reanalysis. The results suggest that differences in temperature between summer and winter can explain a major part of the observed differences in GDP between summer and winter. This finding is in contrast to previous work which concluded that temperature plays at most a minor role for seasonal cycles of GDP. This discrepancy can partly be explained with limited evidence available at the time of earlier studies, inappropriate methods to infer causality that neglected expectations, and possibly a focus on proximate (technology shocks, preference shocks) rather than fundamental drivers of economic fluctuations.

The results also reveal a large diversity across countries and systematic differences between countries in the Northern and in the Southern hemisphere. Given that previous work focused on small and relatively homgeneous subsets of countries, this global heterogeneity can potentially explain some of the discrepancies between my and earlier results. The results suggest an overall positive effect of seasonal temperature on seasonal economic production. Somewhat consistent with this finding, the results also show that economic activity is larger in summer than in winter in a majority of countries, and that the effect of temperature tends to be more positive in the subsample of countries in which production tends to peak in summer than in all other countries.

The effect of seasonal temperature is both significant and economically large. On average differences in seasonal temperature can explain almost all of the differences in seasonal production. To address concerns about causal inference from cross-sectional variation, I state the conditions under which my estimates are unbiased. In robustness tests, I find that the estimated effect of seasonal temperature is robust to including a wide range of control variables, including seasonal differences in precipitation, annual mean temperature, GDP per capita levels, religion, latitude, land area, and variables related to the sectoral composition of an economy, international trade, and international tourism.

This robustness of my main estimates to the inclusion of variables that can also be considered as possible channels through which temperature affects an economy also hints at mechanisms that cannot be primarily responsible for the estimated effects. Using a subsample of 32 European economies and data from EUROSTAT, I examine the effect of seasonal temperature on seasonal GDP and seasonal GVA of different industry groups. The results suggest a significantly positive effect for GDP and for GVA in industries in which production is relatively frequently exposted to ambient temperature, but no significant effect for GVA in all other industry groups, consistent with an effect of temperature on the supply side of the economy.

The results suggest benefits of higher seasonal temperatures for seasonal economic production but should be cautiously interpreted regarding future climate change. Specifically, the results suggest that wherever anthropogenic climate change affects differences in temperature between seasons, economic activity will be reallocated between seasons, increasing or decreasing seasonal differences in GDP. However, the results do not allow conclusions about the extent to which total annual production will be affected by future changes to seasonal or annual temperatures. This latter question has been the focus of a large body of prior literature which tends to agree that an increase in annual mean temperature has a negative effect on GDP in very warm countries and a possibly positive effect in relatively cold countries (e.g. Dell et al. (2012); Burke et al. (2015); Acevedo Mejia et al. (2018); Colacito et al. (2019)).

To quantify the possible seasonal reallocation of economic production under future climate change, I combine my empirical estimates with the results of climate models. The results point to substantial future changes to seasonal economic cycles. Overall, most countries in my sample are projected to see a reallocation of production from winter to summer of up to several percentage points of annual GDP. At the same time, a few countries are projected to see a reallocation from summer to winter. The results also suggest that mitigation of climate change can substantially reduce these reallocations, specifically to about a fourth from RCP8.5 to RCP4.5.

The results overall suggest that temperature should be taken into account in seasonal forecasts of economic production. While this is already the case in some countries (see e.g. Bundesbank (2012, 2014)), my results point to an influence of weather on seasonal economic cycles across a wide range of socio-economic and climatic contexts. Given that climate change will increase seasonal economic cycles in some countries, the results also suggest a future increase in demand for fiscal, monetary, and structural policies that help to smoothen quarterly fluctuations of production and employment. Furthermore, my results suggest that economic development can make economies generally more resilient to the influence of seasonal temperature variability, pointing to possible adaptation.

The results also point to a new avenue of macroeconomic research on the fundamental drivers of fluctuations of GDP, employment, and prices accounting for the deterministic and the stochastic part of temperature variability. The evidence presented here suggests that temperature affects production through productivity shocks, but does not exclude that part of the estimated effects is also due to seasonal shifts in preferences. Disentangling the two with a structural model appears to be one promising research perspective. Furthermore, the analysis revealed that some countries have largest production in winter and others in summer. Future research could examine to what extent these opposite patterns can be explained with economic specialisation and trade.

Previous research has found negative effects of seasonal temperature variability on economic activity (Linsenmeier, 2021). The results in this paper corroborate an influence of seasonal temperature variability on economic production. Furthermore, the results suggest that larger seasonal variability is associated with larger seasonal differences in GDP. While previous research has found that fluctuations of GDP between years have a negative effect on GDP (Ramey and Ramey, 1994), this possible mechanism has not been studied in the context of quarterly or seasonal fluctuations and seems to deserve the attention of future research. Given that future climate change is projected to change seasonal temperature differences, this points to yet another channel through which climate change will affect economic production in the future.

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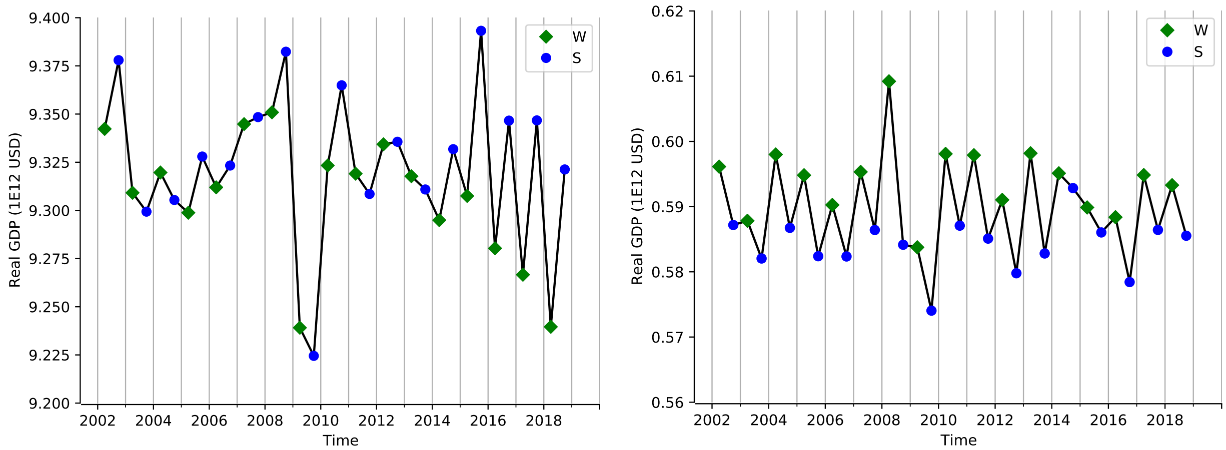
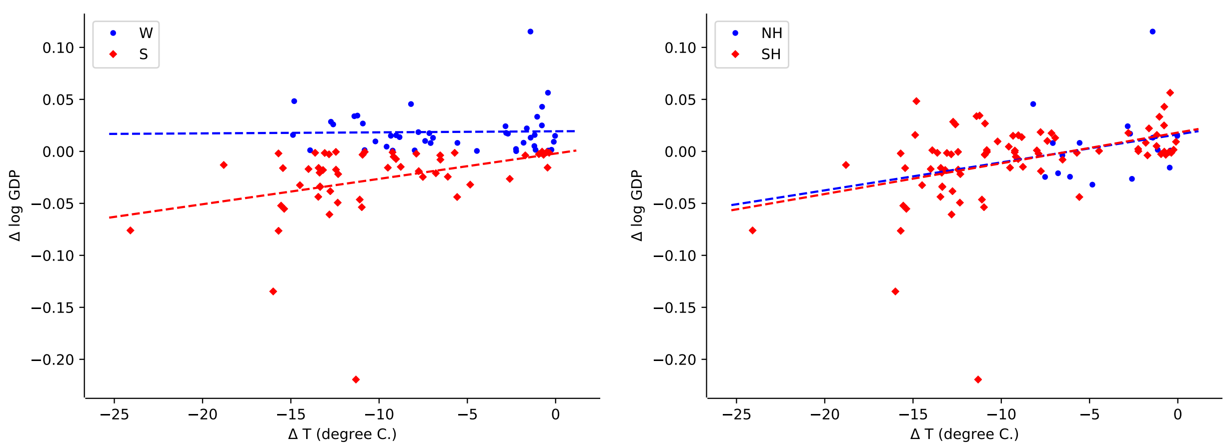
A Additional results

Figure A1. Timeseries of seasonal production: winter (W) and summer (S) for the USA (left) and Brazil (right).



Notes: Note that there is no clear ordering of summer and winter within a calendar year. The order chosen here for visualisation (winter, summer) is arbitrary and does not affect any of the results.

Figure A2. Scatter plot of seasonal differences of temperature and log GDP.



Notes: Colors indicate split of sample into countries with larger output in winter (W) and in summer (S) (left) and countries in the Northern hemisphere (NH) and Southern hemisphere (SH) (right).

Table A1. Results of balancing tests for summer-peak and winter-peak countries.

Peak of temperature in:		W		S		
Variable	Unit	Mean	Std.	Mean	Std.	p-value
Seasonal diff. in log GDP	USD 2010	0.02	0.02	-0.03	0.04	0.000
Seasonal diff. in temperature	deg. C	-6.06	4.66	-9.87	5.36	0.000
Seasonal diff. in precipitation	mm day-1	-0.05	0.06	-0.01	0.05	0.001
Annual mean temperature	deg. C	17.96	6.98	15.00	7.15	0.042
Share of agriculture in GDP	percent	8.52	8.94	7.64	5.99	0.586
Share of manufacturing of GDP	percent	14.75	6.22	15.19	4.65	0.700
Share of exports of GDP	percent	42.49	31.64	46.04	28.91	0.568
Share of imports of GDP	percent	40.94	27.81	51.33	25.55	0.060
Share of tourism receipts of GDP	percent	13.73	18.11	14.95	12.35	0.706
Share of tourism expenditures of GDP	percent	6.81	2.67	6.32	3.59	0.441
Real interest rate	percent	6.99	8.58	6.08	5.47	0.559
Share of Christian population	percent	57.58	35.37	58.76	35.39	0.869
Share of Muslim population	percent	12.56	25.43	23.12	34.70	0.086
log GDP per capita	USD 2010	9.60	1.08	9.64	0.78	0.845
Land area	1E6 km2	12.06	2.61	11.26	2.26	0.114
Latitude	degrees	19.65	28.13	30.91	24.00	0.039
Latitude, absolute value	degrees	27.93	19.70	35.92	15.32	0.031

Notes: There are 55 summer-peak countries (S) and 41 winter-peak countries in the sample. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A2. Results of regressions using a global sample of GDP of countries; different control variables.

Dependent variable:	Δ *log GDP*				
Column	1	2	3	4	5
ΔT	0.0031***	0.0031***	0.0036***	0.0037***	0.0038***
	(0.0008)	(0.0008)	(0.0008)	(0.0009)	(0.0010)
Δ Precipitation	-0.1835**	-0.1811*	-0.1744*	-0.1544**	-0.1555**
	(0.0819)	(0.0955)	(0.0964)	(0.0607)	(0.0657)
Annual mean temperature	0.0000	0.0000	0.0005	-0.0003	0.0001
	(0.0006)	(0.0008)	(0.0009)	(0.0008)	(0.0011)
log GDP pc	0.0158**	0.0158*	0.0139*	-0.0258*	-0.0242
	(0.0078)	(0.0082)	(0.0083)	(0.0146)	(0.0150)
Share of agriculture of GDP	0.0006	0.0006	0.0005	-0.0020	-0.0019
	(0.0012)	(0.0012)	(0.0012)	(0.0015)	(0.0014)
Share of manufacturing of GDP		0.0000	-0.0001	-0.0008	-0.0006
		(0.0008)	(0.0008)	(0.0006)	(0.0006)
Share of exports of GDP				0.0016***	0.0015**
				(0.0006)	(0.0006)
Share of imports of GDP				-0.0019***	-0.0018***
				(0.0006)	(0.0006)
Share of tourism receipts of GDP				-0.0006	-0.0005
				(0.0005)	(0.0006)
Share of tourism expenditures of GDP				0.0029*	0.0030*
				(0.0017)	(0.0018)
Real interest rate				-0.0010	-0.0012*
				(0.0006)	(0.0006)
Share of Christian population	-0.0122	-0.0126	-0.0138	-0.0163	-0.0234**
	(0.0111)	(0.0110)	(0.0105)	(0.0103)	(0.0109)
Share of Muslim population		-0.0010	-0.0042	-0.0066	-0.0106
		(0.0185)	(0.0185)	(0.0166)	(0.0189)
Southern hemisphere SH (dummy)					-0.0184
					(0.0426)
Share of Christian population · SH					0.0510
					(0.0394)
Share of Muslim population · SH					0.0195
					(0.0655)
log Landarea	0.0039***	0.0038***	0.0047***	-0.0015	-0.0017
	(0.0014)	(0.0013)	(0.0014)	(0.0021)	(0.0021)
Latitude			0.0003*	0.0004**	0.0006*
			(0.0002)	(0.0001)	(0.0004)
Intercept	-0.1812*	-0.1804*	-0.1783*	0.3351**	0.3085*
	(0.0956)	(0.0998)	(0.0993)	(0.1624)	(0.1651)
R2	0.35	0.34	0.36	0.52	0.54
R2 adj.	0.30	0.28	0.29	0.42	0.42
N	30 97	96	96	90	90

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3. Results of regressions using a global sample of GDP of countries; different time periods.

Dependent variable:	Δ *log GDP*					
Time period:	1990-2018			2014-2018		
Column	1	2	3	4	5	6
ΔT	0.0029***	0.0031***	0.0262***	0.0034***	0.0035***	0.0213*
	(0.0006)	(0.0008)	(0.0080)	(0.0009)	(0.0009)	(0.0108)
Annual mean temperature $\cdot \Delta T$			-0.0000			-0.0002**
			(0.0001)			(0.0001)
log GDP pc $\cdot \Delta T$			-0.0024***			-0.0014
			(0.0009)			(0.0011)
Δ Precipitation		-0.1835**	-0.1898**		-0.3110***	-0.3283**
		(0.0819)	(0.0809)		(0.1121)	(0.1259)
Annual mean temperature		0.0000	-0.0005		-0.0002	-0.0023**
		(0.0006)	(0.0008)		(0.0007)	(0.0011)
log GDP pc		0.0158**	-0.0066		0.0062	-0.0062
		(0.0078)	(0.0116)		(0.0098)	(0.0129)
Share of agriculture of GDP		0.0006	0.0001		-0.0032**	-0.0025*
		(0.0012)	(0.0011)		(0.0016)	(0.0014)
Share of Christian population		-0.0122	-0.0194**		-0.0318**	-0.0367***
		(0.0111)	(0.0097)		(0.0145)	(0.0124)
log Landarea		0.0039***	0.0030**		0.0052***	0.0042**
		(0.0014)	(0.0013)		(0.0016)	(0.0017)
Intercept		-0.1812*	0.0523		-0.0732	0.0980
		(0.0956)	(0.1223)		(0.1168)	(0.1464)
R2	0.17	0.35	0.43	0.15	0.48	0.53
R2 adj.	0.16	0.30	0.37	0.14	0.43	0.47
N	98	97	97	87	86	86

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A4. Results of regressions using a sample of GVA by industry groups of 35 European economies.

Variable	TOTAL	A	B-E	C	F	G-I	J	K	L	M-N	O-Q	R-U
ΔT	0.0033**	0.0041	0.0063*	0.0033	0.0096**	0.0059	-0.0002	-0.0015	0.0021	-0.0023	-0.0004	0.0015
	(0.0015)	(0.0184)	(0.0031)	(0.0023)	(0.0043)	(0.0039)	(0.0024)	(0.0038)	(0.0015)	(0.0022)	(0.0024)	(0.0032)
Annual mean temperature	-0.0024**	0.0085	-0.0045*	0.0001	0.0020	-0.0062**	-0.0007	-0.0004	-0.0005	0.0034	-0.0020	-0.0001
	(0.0011)	(0.0131)	(0.0023)	(0.0025)	(0.0028)	(0.0024)	(0.0019)	(0.0016)	(0.0008)	(0.0023)	(0.0024)	(0.0020)
log GDP pc	0.0194*	0.1552*	0.0045	0.0338**	0.0938***	0.0540**	0.0317***	0.0093	-0.0136	0.0450***	-0.0249	-0.0236
	(0.0097)	(0.0866)	(0.0153)	(0.0148)	(0.0293)	(0.0221)	(0.0092)	(0.0230)	(0.0139)	(0.0133)	(0.0229)	(0.0291)
Share of agriculture of GDP	0.0000	0.0023	-0.0005	0.0009	0.0147***	0.0051	0.0032**	0.0036	-0.0016	0.0027*	-0.0019	-0.0017
	(0.0011)	(0.0096)	(0.0018)	(0.0012)	(0.0046)	(0.0034)	(0.0012)	(0.0048)	(0.0028)	(0.0014)	(0.0027)	(0.0044)
Share of Christian population	-0.0027	0.0044	-0.0048	0.0084	0.0714	-0.0337	-0.0224	0.0755	-0.0257	-0.0226	-0.0164	-0.0542
	(0.0151)	(0.2089)	(0.0254)	(0.0201)	(0.0544)	(0.0301)	(0.0163)	(0.0531)	(0.0327)	(0.0213)	(0.0295)	(0.0416)
log Landarea	0.0048***	0.0060	0.0077**	0.0090***	0.0044	0.0061**	0.0038*	0.0039	-0.0033	0.0068***	0.0028	0.0010
	(0.0016)	(0.0166)	(0.0028)	(0.0028)	(0.0044)	(0.0030)	(0.0019)	(0.0032)	(0.0021)	(0.0023)	(0.0037)	(0.0047)
Intercept	-0.1971*	-1.8608	0.0065	-0.4213**	-1.0674***	-0.5204**	-0.3451***	-0.2080	0.2258	-0.5862***	0.2768	0.3001
	(0.1096)	(1.1324)	(0.1839)	(0.1831)	(0.3833)	(0.2462)	(0.1236)	(0.3249)	(0.1895)	(0.1785)	(0.2492)	(0.3294)
R2	0.55	0.18	0.41	0.44	0.47	0.40	0.39	0.20	0.15	0.39	0.12	0.13
R2 adj.	0.45	0.00	0.29	0.32	0.35	0.27	0.26	0.02	-0.03	0.26	-0.06	-0.06
N	35	35	35	35	35	35	35	35	35	35	35	35

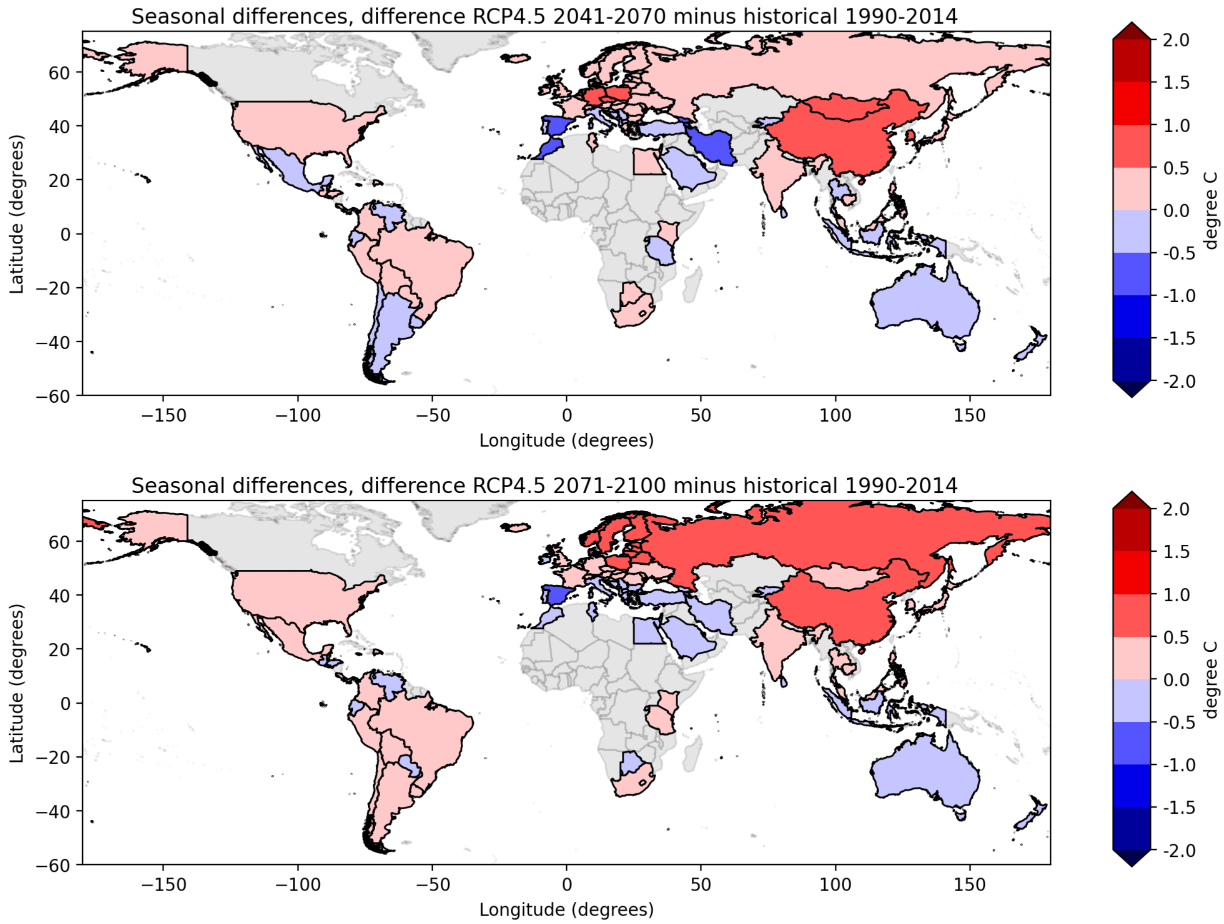
Notes: A: Agriculture, forestry and fishing, B-E: Industry (except construction), C: Manufacturing, F: Construction, G-I: Wholesale and retail trade, transport, accommo., J: Information and communication, K: Financial and insurance activities, L: Real estate activities, M-N: Professional, scientific and technical activit., O-Q: Public administration, defence, education, hum., R-U: Arts, entertainment and recreation; other serv. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A5. Results of regressions using a global sample of GDP of countries using differences between quarter with maximum and mimnimum temperature for identification.

Dependent variable:	Δ *log GDP*				
Sample:	All countries			S	W
Column:	1	2	3	4	5
ΔT	0.0071***	0.0082***	0.0647***	0.0054***	0.0017
	(0.0012)	(0.0014)	(0.0157)	(0.0018)	(0.0011)
Annual mean temperature · ΔT			-0.0001		
			(0.0001)		
log GDP pc · ΔT			-0.0058***		
			(0.0017)		
Δ Precipitation		-0.1279	-0.1494	-0.0570	-0.1091
		(0.1403)	(0.1256)	(0.1892)	(0.1147)
Annual mean temperature		-0.0006	0.0016	-0.0017	0.0013
		(0.0019)	(0.0026)	(0.0019)	(0.0010)
log GDP pc		-0.0278*	0.0482*	0.0082	-0.0164
		(0.0160)	(0.0255)	(0.0233)	(0.0147)
Share of agriculture of GDP		0.0010	0.0028	0.0102**	-0.0026
		(0.0028)	(0.0025)	(0.0049)	(0.0022)
Share of Christian population		0.0454	0.0736***	0.0708**	0.0062
		(0.0299)	(0.0237)	(0.0305)	(0.0202)
log Landarea		-0.0081***	-0.0059**	-0.0107**	-0.0006
		(0.0031)	(0.0026)	(0.0046)	(0.0016)
Intercept		0.2841	-0.5224**	-0.0470	0.1248
		(0.1905)	(0.2505)	(0.2400)	(0.1841)
R2	0.28	0.43	0.56	0.51	0.23
R2 adj.	0.27	0.38	0.52	0.44	0.05
N	98	97	97	60	37

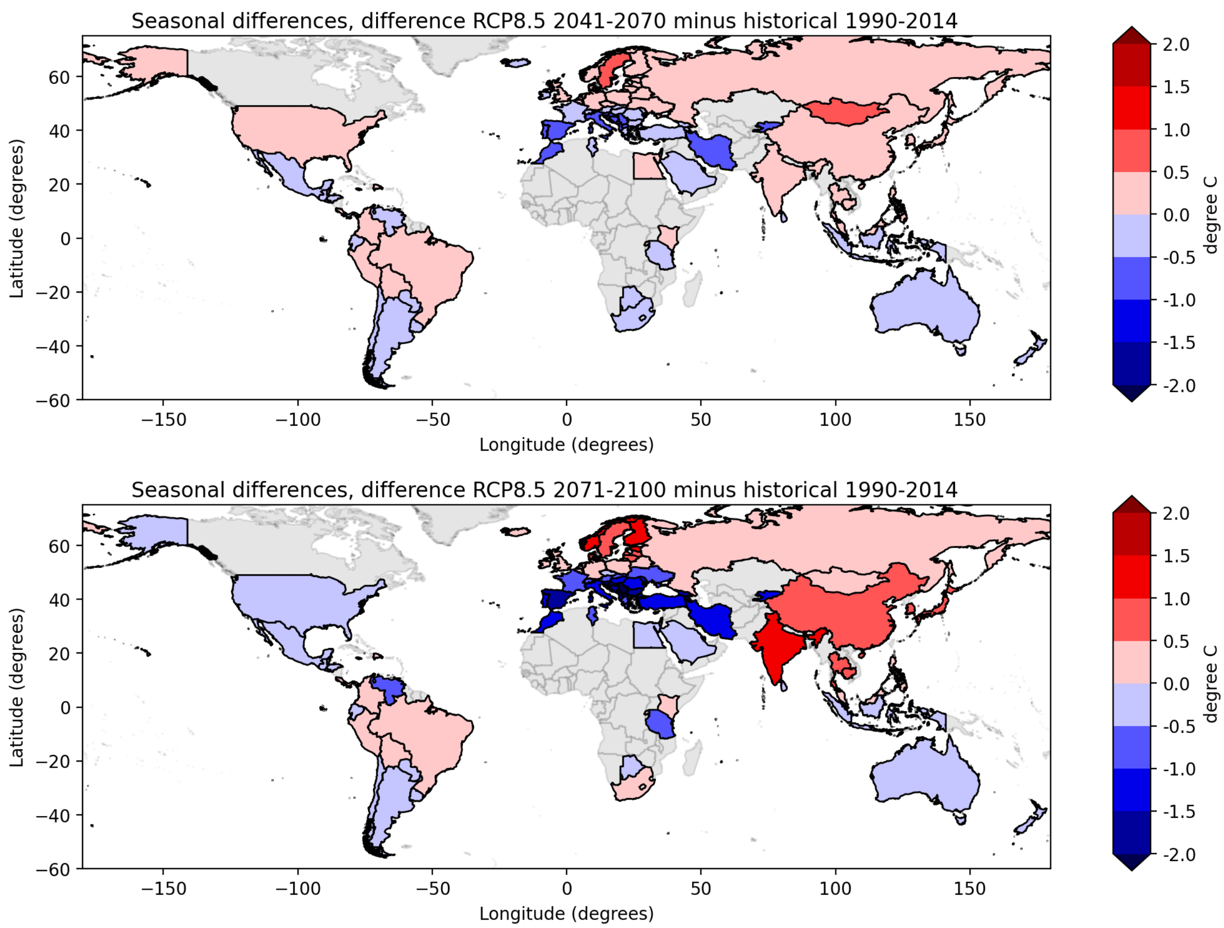
Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure A3. Future projections of ΔT for RCP4.5 for 2041-2070 and 2071-2100.



Notes: Seasonal differences calculated as winter minus summer. Positive values mean that temperature in winter is projected to increase more than temperature in summer.

Figure A4. Future projections of ΔT for RCP8.5 for 2041-2070 and 2071-2100.



Notes: Seasonal differences calculated as winter minus summer. Positive values mean that temperature in winter is projected to increase more than temperature in summer.