At boiling point: The propagation and amplification of heat shocks in global business groups

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Abstract

This paper shows that local heat shocks spill over to other regions through multinational firms' internal networks. Using novel global data on the headquarter-affiliate-relationships for a quarter of a million business group firms operating in 32 countries between 2002 to 2012, we find that local heat shocks from longstanding affiliates in countries with hot climates translate into a strong decline in the economic output of headquarter firms that are not directly affected by any heat shock. The vertical spillovers incurred at the headquarter level are higher than the corresponding first order effect at the local subsidiary level, suggesting that firms' internal networks can substantially amplify climate change related risks.

1 Introduction

The body of evidence for the economic costs of climate changes is overwhelming. Extreme weather and high temperatures in particular have been identified as one of the main drivers that strongly lower local economic output in many world regions (Dell et al. 2014, Burke et al. 2015, Kalkuhl and Wenz 2020, Kahn et al. 2021, Kotz et al. 2022). At the same time, the world economy has grown increasingly integrated. As a result, local temperature shocks may not only lead to economic declines for firms and sectors in the affected region but also in distant other regions (Wenz and Willner 2022). Such spillovers are particularly likely in multinational business groups, which are an important pillar of the global economy. For instance, multinational companies account for around a third of total global output and half of global exports (OECD 2018). These companies integrate supply, production and sales within their firm networks that can span different economic sectors, world regions and climatic zones (Altomonte and Rungi 2013). Despite their economic importance, the potential impacts of climate change on global business groups and the potential transmission of shocks within their networks has received little attention by both researchers and policymakers.

The extent to which climate related risks can spill over within networks of firms is an empirical question. On the one hand, local temperature shocks might be absorbed in geographically diversified firm networks of multinationals. The adverse effects of heat on economic activity of an affiliate firm in one region in a given year could be compensated by other affiliates experiencing more favorable temperatures elsewhere. On the other hand, given the compelling evidence that heat distorts individual, firm, and aggregate economic performance, it is unclear whether multinational firms are flexible enough to effectively recompose their supply, production, and sales mix in case of ever more frequent heat events. In fact, the broader economics literature on firm networks suggests that firm-level idiosyncratic shocks often propagate across firms, sectors and countries (Cravino and Levchenko 2017, Giroud and Mueller 2019).

This paper examines spillovers of local heat shocks within the networks of more than a quarter of a million business group firms operating in 32 countries. We build a data set that consistently combines information on firm ownership and location with financial data to recover the spatial network of multinational firms across time and climate zones. Our focus is on long-term headquarter-affiliate-relationships that are of particular strategic importance in firm networks. We first replicate previous studies by assessing the direct impact of local heat events on economic output. Specifically, we quantify the adverse impact of yearly exogenous variation in local heat from 2002 to 2012 on the output of affected affiliates in our business group sample. Subsequently, we test whether the weighted local heat shocks from affiliates translate into a decline in the economic output of the headquarter firms that are not directly affected by any heat shock. In doing so, we provide new evidence on vertical spillovers that occur upstream, i.e. from a subsidiary to the headquarter.

We find that an additional day with temperature above 32°C leads to a drop in the locally affected affiliates' sales by 1.3%. This direct adverse effect is driven by firms that operate in countries with hot climates, i.e. average yearly temperature above 13°C. Furthermore, we find that longstanding affiliates hit by heat locally impose significant output losses on their headquarters. More specifically, we find that the weighted local heat shocks from affiliates translate into an on average drop in headquarter revenues by 4.2% per additional heat day. The finding that transmitted shocks are more sizeable than the initial local shocks suggests that heat shocks may be amplified by the complex, interlocking supply, production, and sales networks of multinationals.

The contributions of this study relate to two fields of research. First, in the field of climate economics, our study contributes to a better understanding and more comprehensive assessment of the true cost of climate change, which is crucial for the evaluation of optimal climate policy. In the first place, it provides estimates for the direct impacts of temperature on output in a global context, measured at a granular scale. Global evidence across heterogeneous climatic regions is scarce due to limitations with respect to econometric identification and data availability. Cross-country studies use data at the sector, county, state or country level and thus cannot adequately control for heterogeneous firm responses (e.g. Burke et al. 2015, Burke and Tanutama 2019, Kalkuhl and Wenz 2020, Kahn et al. 2021). Studies that do use firm data are often constrained to analyzing a single sector in a specific country (e.g. Zhang et al. 2018). This paper attempts to resolve these issues by delivering a cross-country analysis based on global firm data that accounts for firm, sector and country heterogeneity. The results confirm previous findings of a non-linear temperature-output relationship with strong responses at high temperatures for a cross-country sample of business group firms that comprises different world regions and climatic zones. We also find that responses to heat are particularly robust and driven by companies that operate in countries with average yearly temperature above 13°C. In addition, our study illuminates a new facet in the climate-economy relationship by showing that heat-induced economic losses are not necessarily confined to the affected area but can spill over within firm networks, thereby amplifying the total loss. Such cross-border spillover effects, although potentially critical for damage functions, have remained largely under-investigated in the climate-economy literature so far and are lacking from estimates of the cost of climate change (Dell et al. 2014, Auffhammer 2018). Our findings contribute to recent sector-level studies that show that local temperature induced losses can cascade through value chains (Wenz and Levermann 2016, Kuhla et al. 2021).

Second, our paper contributes to a growing literature in macro-, and financial economics that studies the transmission of shocks throughout the economy. The economic response in production networks to external shocks is a long-standing issue in theoretical and empirical studies (Bena and Erel 2017). Our paper complements recent empirical research showing that natural disasters propagate in production networks (Barrot and Sauvagnat 2016), that sales growth between subsidiaries and headquarters co-move and that source-country shocks are transmitted to foreign affiliates (Cravino and Levchenko 2017), that network structures can provide additional resilience to their subsidiaries (Giroud and Mueller 2019) and that customer firms respond to perceived changes in their suppliers' climate-risk exposure (Pankratz and Schiller 2021).

The remainder of this paper is structured as follows: Section 2 details the identification strategy. Section 3 describes the data. Section 4 presents the empirical results. Section 5 concludes with a discussion of the results.

2 Empirical framework

Similar to Barrot and Sauvagnat (2016), we conduct a two-step analysis to estimate the impact of heat shocks on global business groups. In a first stage, we estimate the direct effect of extreme local temperatures on firm output for a global sample of affiliate firms that are part of a business group at some point in time. In a second step, we analyze how temperature shocks at the subsidiary level affect economic outcomes at the level of headquarters.

2.1 Direct temperature effects on affiliate output

To estimate the direct effect of extreme local temperatures on the output (proxied by operation revenue) of affiliate firms, we adopt the well established semi-parametric approach by Deschênes and Greenstone (2011) that allows temperature to affect economic output in a non-linear manner without making assumptions about the functional form of their relationship (see also Deryugina and Hsiang (2014) and Auffhammer (2018)). To this end, we divide the annual temperature distribution into $m = 1 \ldots 10$ bins. Each temperature bin m corresponds to the number of days per year that fall into the given category. The binning preserves the daily variation in temperature which is important to capture the impact of heat days on economic output (Dell et al. 2014). The bins are constructed at a 6-7°C width with temperatures below minus 12°C at the lower end and temperatures above 32°C at the upper end. The 16-20°C bin is our reference category.

For firm i in year t, we employ the following log-linear regression specification:

$$y_{it} = \sum_m \beta_1^m T_{it}^m + \delta W_{it} + D_{it} + X_{it} + \epsilon_{it}; \tag{1}$$

where y_{it} is the natural logarithm of operating revenue and T_{it}^m is the number of days in year t where firm i experienced temperatures that fall in bin m. In addition, we control for linear and quadratic effects of total annual precipitation in vector W_{it} (compare e.g. Blanc and Schlenker (2017), Burke and Emerick (2016), and Kalkuhl and Wenz (2020)). To account for the potential bias arising from past weather shocks (Zhang et al. 2018, Burke and Tanutama 2019, Kotz et al. 2022), we also include one years lags of precipitation and temperature bins in W_{it}.

We exploit the panel structure of our data to isolate the effect of temperature on economic output from any time-invariant and time-varying factors that could be associated with temperature and economic output (Hsiang 2016, Blanc and Schlenker 2017, Kolstad and Moore 2020). To this end, we first include vectors of fixed effects D_{it}. Included are firm fixed effects, country-industry fixed effects (accounting for sector and country specific characteristics such as technology), sector-year fixed effects (to account for overall technological progress or changes in input or output prices), and country-year fixed effects (capturing country-specific annual shocks such as economic progress). Second, in our preferred specification, we also include a set of control variables X_{it} to account for important time-variant developments at the firm level, namely total assets, return on assets and firm age. Since these variables might be affected by weather and are potentially endogenous, we follow Barrot and Sauvagnat (2016) and interact binary year indicators with terciles of the variables measured pre-treatment.

Our main identifying assumption is that variation in temperature is random conditional on the set of fixed effects (Deschênes and Greenstone 2007, Deschênes and Greenstone 2011, Auffhammer 2018). Then, the coefficient β_1^m is a semi-elasticity that measures the marginal effect of an additional day in temperature bin m relative to a day in the 16-20°C bin.

2.2 Indirect temperature effects on headquarter output through firm network

To test whether the local heat shocks from affiliates are transmitted to the headquarter firms by affecting their output as well, we examine whether headquarter revenue responds to linkage-weighted local temperature shocks that occur at the subsidiary level. More specifically, similar to Giroud and Mueller 2019, each local weather shock at the subsidiary level is weighted by the affiliate's annual share in total operating revenue of the entire business group to which it belongs. Accordingly, a local temperature shock affecting an affiliate i matters more for a headquarter firm h if the respective parent firm is more exposed to affiliate i as measured by the revenue of firm i relative to other firms the business group h owns.

We estimate the following equation:

$$y_{ht} = \sum_m \beta_1^m T_{ht}^m + \sum_m \beta_2^m TA_{ht}^m + \delta W_{ht} + D_{ht} + X_{ht} + \epsilon_{ht}; \tag{2}$$

where T_{ht}^m is the number of days in year t where the headquarter firm h experiences temperatures that falls in bin m; TA_{ht}^m is the sum of weighted temperature bins with $TA_{ht}^m = \sum_i w_{hit} T_{hit}^m$, where w_{hit} is the weight for each affiliate i of parent firm h in year t and T_{hit}^m is the respective temperature experienced by affiliate i in each bin m. As in equation 1, W_{ht} comprises linear and quadratic effects of precipitation (and, in our preferred specification, past weather shocks, i.e. lagged precipitation and temperature bins). D_{ht} holds a set of fixed effects. X_{ht} includes control variables at the headquarter-level, namely total assets, return on assets and firm age but also the number of affiliates the firm holds (to control for the size of the firm network). Again we generate these controls by interacting binary year indicators with terciles of the variables measured pre-treatment (Barrot and Sauvagnat 2016).

3 Data

We construct a novel database that is suitable for assessing the impacts of temperature variation on business groups in a global cross-country setting. For the period of 2002-2012, we bring together three sources of data: Firm financial data and information on firm ownership from ORBIS and weather data from the WATCH-Forcing-Data-ERA-Interim meteorological data set (WFDEI).

3.1 Firm financial and location data

Our main source of data is the ORBIS database as provided by Bureau van Dijk (BvD). ORBIS compiles firm data from administrative sources, such as detailed balance sheets, income statements, and profit and loss accounts. The database is constantly being updated and particularly suitable for cross-country comparisons: Information on firm financials and ownership is harmonized across countries and delivered in a global standard format. The financial data that we use was retrieved by BvD in the last week of November 2015. The data comprises all firms above total assets of 2 million Euro, a turnover of one million Euro, or a total number of 15 employees in 2015. This corresponds to a sample of around 12.5 million firms. We employ unconsolidated financial data from local registry filings to ensure a high quality of the raw information. Industries are classified according to their four-digit industry NACE Rev. 2 codes.

We then follow a thorough three-step procedure of data cleaning that is based on Gopinath et al. (2017). First, we account for reporting mistakes and drop observations with missing information or implausible values. If data is missing for one year between two periods with reported values, we interpolate data for one period. Second, we assess the internal consistency of the balance sheet data. For example, we calculate the sum of tangible fixed assets, intangible fixed assets, and other fixed assets as a ratio of their respective aggregate, i.e. total fixed assets. [1] We then estimate the distribution of this ratio and remove extreme values (below the 0.1 percentile and above the 99.9 percentile. Third, we winsorize all variables at the 1 and 99 percentiles. In order to properly identify shocks in business groups, we drop any firms that are part of the financial services industries and government-related sectors (Bena and Erel 2017).

All nominal variables used in our analysis are reported in thousands of Euros and deflated with a yearly GDP price deflator as retrieved from the Worldbank.[2] This procedure ensures that the growth rates of the variables are not driven by price changes (Gal 2013). After deflating all financial covariates over time, we account for price differences across countries and then convert all variables into a common currency (USD). In order to mitigate the influence of fluctuating exchange rates, we fix the exchange rate at the middle of the sample period, in 2007 (Gal 2013).

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[1] This process is also applied to the following aggregates: total assets, total current assets, total shareholder funds and liabilities.

[2] As retrieved from https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS

We then identify latitudes and longitudes for each firm location. For this step, we apply algorithms provided by OpenCage and Google[3] to the address data contained in ORBIS (street, postal code, city, region and country) to obtain each geographic location. For each country, we conduct a thorough testing process and assess (i) general quality of the match and (ii) precision based on the respective indicators provided by each algorithm. We also compare geo-coded output on location and addresses with the address data in ORBIS and own identification done via Google Maps and Open Street Maps. We then account for systematic matching errors and adjust the matching algorithms accordingly. For 94% of the matched sample, the precision is very high, i.e. within a grid cell radius of less than 2 km. For 4%, the grid cell radius is less than 15 km. We remove any firms with a grid cell radius above 15 km (2%). Given that the spatial correlation of weather is high, especially in small geographical grid cells, measurement error should be small (Auffhammer et al. 2013).

3.2 Weather data

Weather data is obtained for the period of 2002-2012 from the WATCH-Forcing-Data-ERA-Interim meteorological data set (WFDEI, Weedon et al. (2018) and Dee et al. (2011)). This dataset provides extensive coverage on a complete global grid all while providing the variation of high frequency daily average weather data.[4] The temperature data are converted into Celsius and sorted into bins. Annual precipitation is obtained by adding snowfall to rainfall data, converted into mm/day and aggregated to a full year.[5]

We then match the geographic location of each firm in ORBIS with the corresponding 0.5x0.5 grid cell in the WFDEI data. We also match each firm location with its respective administrative area as contained in the GADM database of Global Administrative Areas.[6] Matching and mapping exercises are conducted via shape files and algorithms in GNU R. Hence, we obtain for each firm-year-combination in ORBIS the average weather in the respective cell.

For the matched ORBIS dataset, Figure 1 plots the distribution of unique firm observations along with the temperature data on a world map. Figure 2 zooms into Europe.

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[3] Available on https://opencagedata.com/ and https://developers.google.com/maps/documentation/geocoding/

[4] ERA-interim reanalysis data combines information from ground stations, satellites and other sources with a climate model to create gridded weather data and extend global coverage. This data is then bias corrected such that the monthly temperature means correspond to observational data. In contrast, many other datasets either suffer from incomplete coverage in certain world regions and/or deliver only monthly weather averages. We refer to Dell et al. (2014) and Auffhammer et al. (2013) for an overview and discussion of different weather data types in the context of econometric analyses.

[5] The data was provided by the Inter-Sectoral Impact Model Intercomparison Project (https://www.isimip.org/). The steps were conducted via Python.

[6] The data can be retrieved from https://gadm.org/

Administrative areas are presented according to the GADM classification system. For each area, we calculate (i) the average daily temperature based on the corresponding grid cells and (ii) the total number of firms. Black dots constitute administrative areas with less than 10,000 firms. Bubbles represent areas with up to more than 70,000 firms. Regions are ranked with respect to their heat exposure using the average number of days with average temperature above 27°C in 2002-2012. The dataset covers a wide range of climatic zones. As it is common in ORBIS, data availability differs substantially across world regions. While most firms are concentrated in European countries, the sample still covers firms from several non-European countries.

We then apply the three country-based criteria established by Cravino and Levchenko (2017) to construct data that is suitable for a global analysis of firm networks in ORBIS: (i) countries need to have at least 750 firms on average in 2002-2012, (ii) aggregate revenues in ORBIS need to cover at least 40% of aggregate economic output and (iii) the correlation between the growth rates in GDP as measured by the Worldbank and in aggregate revenues in ORBIS needs to be above 0.50. We limit our sample to the 32 countries that jointly meet these criteria.[7] We consider this restriction crucial for obtaining empirically meaningful results both in terms of a consistent global analysis of business groups and the analysis of shock transmissions within them.

For the heterogeneity analysis, we divide our sample broadly along the lines of the standard Koeppen-Geiger climate classification system (Beck et al. 2018) and define countries with average yearly temperature above 13°C as having a moderate to hot climate. For the period of our analysis, this definition applies to 10 out of 32 countries in the sample.[8]

3.3 Ownership data

we draw on aus dem Moore et al. (2019) to consistently identify business groups based on the raw information on firm ownership in ORBIS. In principle, firms with more than 50.01% ownership shares are linked until the top of the command chain is reached. This allows the identification of each firm belonging to a certain network along with the network's global ultimate owner (GUO). For a detailed description of the methodology we refer to aus

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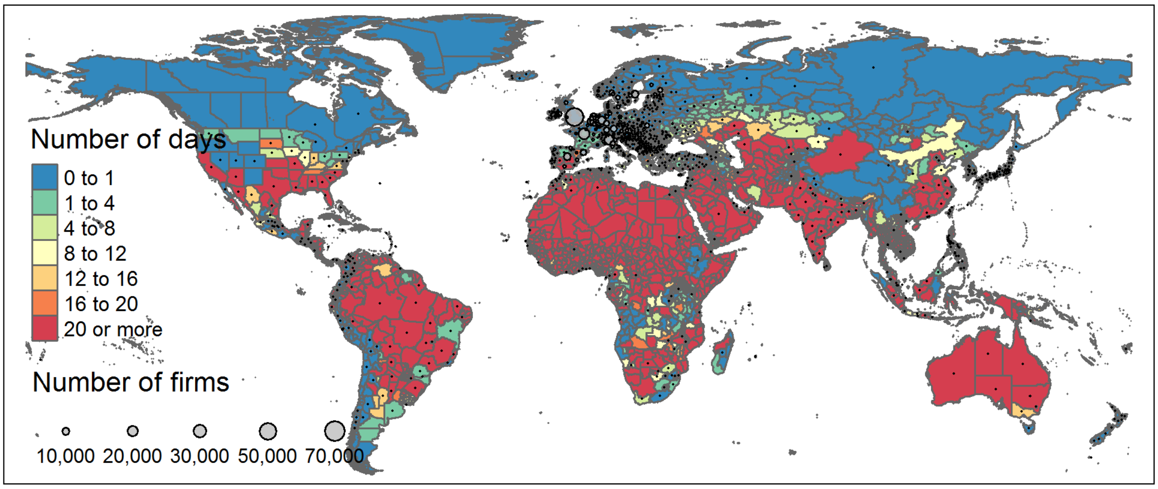
[7] The selected countries are Austria, Australia, Belgium, Bulgaria, the Czech Republic, Germany, Estonia, Spain, Finland, France, Great Britain, Greece, Croatia, Hungary, Ireland, Italy, Japan, South Korea, Lithuania, Latvia, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Sweden, Singapore, Slovenia, Slovak Republic, Turkey and Ukraine.

[8] The selected countries for the Southern sample are Australia, Bulgaria, Croatia, Greece, Italy, Portugal, Romania, Singapore, Spain and Turkey. This corresponds for instance to countries with mostly dry or hot summer climates under the Koeppen-Geiger classification (Beck et al. 2018).

Figure 1: Firm coverage and temperature distribution: World



dem Moore et al. (2019). The novelty of this approach is that, unlike the static approaches employed in the vast majority of empirical studies, the data allows to track ownership relations across time, i.e. for each firm and each year in 2002-2012. Many empirical studies have used time-invariant information based on the last year of the panel thus introducing a potentially strong measurement error.

However, the yearly ownership data contains substantial amounts of noise as the data in ORBIS is constantly updated and extended (aus dem Moore et al. 2019). Missing information over longer periods of time can impede the proper tracking of network structures and severely hamper the identification of shock transmission (Cravino and Levchenko 2017), e.g. through unobserved changes in ownership.

To address the constant updating of ownership data contained in ORBIS and to account for potential missing information over longer periods of time, we clean the ownership data in various steps. First, we fill in ownership gaps if the information before and after the gap is identical.[9] This is done for up to four consecutive years. The vast majority of observations recuperated from this interpolation stems from one-year gaps. Second, we require firms to report at least ownership information for one year meaning that they are either a subsidiary and/or a GUO at some point in time and thus discard any firms with continuously missing information.

Summary statistics are reported in Table 1. It shows that the final sample contains around a quarter of a million firms (Column 1) that at some point between 2002 and 2012 are either

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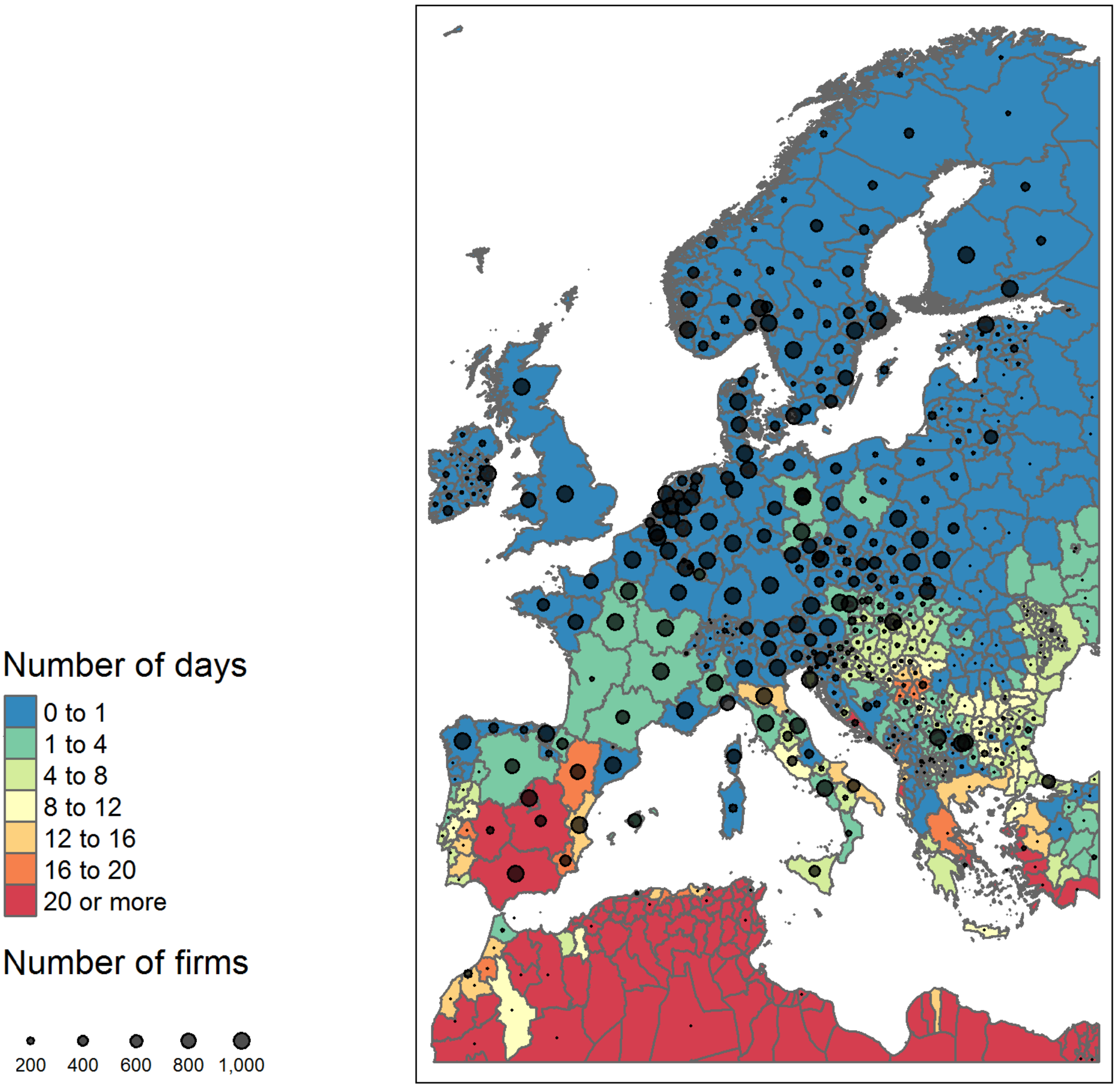
[9] For instance, if a subsidiary is owned by the same firm in the years 2002 and 2004, but the information in the year 2003 is missing, we take this firm as the respective GUO in year 2003.

Figure 2: Firm coverage and temperature distribution: Europe



a subsidiary (Column 2) and/or a GUO (Column 3). The sample is dominated by firms operating in European countries (around 240,000) but still retains around 10,000 firms from the rest of the world and covers a range of climatic zones.

In the spillover analysis, we have a particular focus on relationships where in the period of 2002-2012 a subsidiary has (i) full ownership information and (ii) is owned by the same GUO. While this restriction reduces sample size, it allows us to focus specifically on the transmission of shocks withing long-standing networks between affiliates and GUOs based on high panel data quality. The "long-standing relationship" sample still contains more than 5,100 GUOs that own a total of around 105,000 subsidiaries.

Table 1: Summary statistics: Firm observations

	# Obs	# Firms
Total	1,971,108	250,767
Subsidiaries	1,184,481	213,931
Global ultimate owners (GUOs)	253,839	67,474
Independent	532,788	172,030

Note: Number of subsidiary firms plus number of GUO firms exceeds number of total firms as firms can be subsidiaries and GUOs at different points in time.

4 Results

4.1 Effects on directly affected affiliate firms

Table 2 presents the results for the direct effect of temperature on affiliate output proxied by operating revenue for three specifications with increasing stringency. For our most stringent and preferred specification (3) with firm-level control variables and lagged temperature and precipitation, effects for the hot section of the temperature spectrum are significant at the 5% level for temperatures between 27 and 32°C and above 32°C. In economic terms, the magnitude of the effect of extreme temperature days are important. Relative to a day in the 16-20°C bin, an extra day with temperature above 32°C decreases output by 1.3% (0.1% for temperature between 27-32°C). Coefficients for the cold section of the temperature spectrum are negative, but largely insignificant.

We subsequently examine whether the response of output to local temperature shocks varies by climate regions. Table 3 compares our baseline estimates (1) with estimates for subsamples of ”hot” countries (with average yearly temperature above 13°C) (2) and ”cold” countries (with average yearly temperature below 13°C) (3). For the sample of comparatively hot countries, effects for three temperature bins of the hot part of the spectrum are highly significant at the 1% level (21-27°C bin, 27-32°C bin, and ¿32°C bin). Again, the magnitude for the coefficient of extreme heat days is economically important. Relative to a day in the 16-20°C bin, an extra day with temperature above 32°C decreases output by 1.6% (0.14% for the 27-32°C bin and 0.06% for the 21-27°C bin). Compared to the results for the full sample (1.26%), the effect is more pronounced in magnitude. For the Northern sample, we do not find any evidence for temperature effects.

In sum, our findings suggest that temperature responses at the global level appear to be driven by differences in long-term climate exposure. Strong negative effects from hot temperatures are driven by firms operating in countries with relatively hot climates. Only shocks

Table 2: Direct temperature effects on output of affiliated firms

	(1)	(2)	(3)
< - 12°C	-0.0005	-0.0009	0.0001
	(0.0007)	(0.0007)	(0.0006)
≥ - 12°C; ≤ - 7°C	-0.0009*	-0.0011**	-0.0007
	(0.0005)	(0.0005)	(0.0005)
> - 7°C; ≤ - 1°C	-0.0004	-0.0007**	-0.0003
	(0.0004)	(0.0004)	(0.0003)
> - 1°C; ≤ 4°C	-0.0002	-0.0005	-0.0002
	(0.0003)	(0.0002)	(0.0003)
> 4°C; ≤ 10°C	-0.0001	-0.0003	-0.0001
	(0.0002)	(0.0002)	(0.0002)
> 10°C; ≤ 16°C	0.0001	0.0000	0.0000
	(0.0002)	(0.0002)	(0.0002)
> 21°C; ≤ 27°C	-0.0002	-0.0002	-0.0002
	(0.0002)	(0.0002)	(0.0002)
> 27°C; ≤ 32°C	-0.0011***	-0.0011***	-0.0010**
	(0.0004)	(0.0004)	(0.0004)
> 32°C	-0.0113**	-0.0127***	-0.0128**
	(0.0048)	(0.0046)	(0.0050)
precipitation	2.24	1.31	1.59
	(1.619)	(1.577)	(1.567)
precipitation_sq	-37.39	-26.43	-21.64
	(39.831)	(39.020)	(38.872)
Firm FE	Yes	Yes	Yes
Year x country FE	Yes	Yes	Yes
Country x industry FE	Yes	Yes	Yes
Year x industry FE	Yes	Yes	Yes
Firm-level control variables	-	Yes	Yes
Temperature t-1, precipitation t-1	-	-	Yes
Observations	1,511,588	1,511,588	1,287,622

Standard errors (in parentheses) are clustered at the firm level.
* p<0.10, ** p<0.05, *** p<0.01

Table 3: Heterogeneity in temperature effects on output of affiliated firms

	Baseline	Southern Countries	Northern Countries
	(1)	(2)	(3)
$<$ - 12°C	0.0001	0.0052	0.0001
	(0.0006)	(0.0034)	(0.0007)
$\geq$ - 12°C; $\leq$ - 7°C	-0.0007	-0.0019	-0.0006
	(0.0005)	(0.0015)	(0.0006)
$>$ - 7°C; $\leq$ - 1°C	-0.0003	-0.0001	-0.0002
	(0.0003)	(0.0007)	(0.0004)
$>$ - 1°C; $\leq$ 4°C	-0.0002	-0.0005	0.0001
	(0.0003)	(0.0005)	(0.0003)
$>$ 4°C; $\leq$ 10°C	-0.0001	0.0000	0.0001
	(0.0002)	(0.0004)	(0.0003)
$>$ 10°C; $\leq$ 16°C	0.0000	0.0004	0.0000
	(0.0002)	(0.0003)	(0.0002)
$>$ 21°C; $\leq$ 27°C	-0.0002	-0.0006**	-0.0001
	(0.0002)	(0.0003)	(0.0003)
$>$ 27°C; $\leq$ 32°C	-0.0010**	-0.0014**	-0.0004
	(0.0004)	(0.0006)	(0.0006)
$>$ 32°C	-0.0128**	-0.0158***	-0.0064
	(0.0050)	(0.0057)	(0.0098)
precipitation	1.59	1.77	.23
	(1.567)	(3.609)	(1.749)
precipitation_sq	-21.64	29.67	-3.42
	(38.872)	(137.131)	(40.038)
Firm FE	Yes	Yes	Yes
Year x country FE	Yes	Yes	Yes
Country x industry FE	Yes	Yes	Yes
Year x industry FE	Yes	Yes	Yes
Firm-level control variables	Yes	Yes	Yes
Temperature t-1, precipitation t-1	Yes	Yes	Yes
Observations	1,287,622	398,034	889,588

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.01

from extreme heat, i.e. temperatures above 32°C, appear to be economically meaningful. This evidence for a comprehensive sample of 32 countries is in line with previous firm level studies that focus on specific countries and sectors. For instance, Zhang et al. (2018) detect for the Chinese manufacturing sector an inverted-U-shape relation, strong negative effects of extreme heat and differences among comparatively hot and cold sub-national regions. Similar effects have been found among world regions by studies using comprehensive county- and country-level data (Burke et al. 2015, Burke and Tanutama 2019).

4.2 Spillover of affiliate-level temperature shocks on headquarter firms

Table 4: Spillover effect of temperature shocks to affiliate firms on the output of headquarter firms

	(1)
< - 12°C	0.0122
	(0.0124)
≥ - 12°C; ≤ - 7°C	-0.0008
	(0.0045)
> - 7°C; ≤ - 1°C	0.0017
	(0.0014)
> - 1°C; ≤ 4°C	0.0007
	(0.0009)
> 4°C; ≤ 10°C	0.0012
	(0.0007)
> 10°C; ≤ 16°C	0.0008
	(0.0006)
> 21°C; ≤ 27°C	0.0009
	(0.0008)
> 27°C; ≤ 32°C	0.0010
	(0.0009)
> 32°C	-0.0421**
	(0.0213)
precipitation	-6.87
	(8.223)
precipitation_sq	54.52
	(212.729)
Firm FE	Yes
Year x country FE	Yes
Country x industry FE	Yes
Year x industry FE	Yes
Firm level control variables	Yes
Temperature, precipitation (headquarter)	Yes
Temperature t-1, precipitation t-1 (subsidiary)	Yes
Observations	36,302

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.01

The results presented in Table 4 show that extreme temperature shocks of subsidiary firms induce output losses at the headquarter level. These estimates are based on temperature shocks to subsidiary firms operating in hot climates. Relative to a day in the 16-20°C bin, an additional day with temperature above 32°C at the subsidiary level decreases annual output at the headquarter level by 4.2% and the effect is significant at the 5% percent level. Compared to the local effect on business group firms in the Southern sample (1.6%) reported in Table 3, the transmission effect of extreme heat days at the headquarter level is clearly more pronounced in magnitude. This finding suggests that output losses due to extreme temperatures can be amplified by economic linkages within firm networks.

5 Conclusion

Recent studies on climate economics have aimed to substantially improve damage estimates of climate change. This paper contributes to this effort by shedding new light on a potentially important cost driver: The transmission of temperature shocks within global business groups. We show that headquarter output falls by about 4% if affiliated firms of the business group are exposed to an additional day with local temperatures above 32°C. Importantly, losses incurred at the headquarter level are higher than the corresponding first order effect at the local subsidiary level, which indicates that temperature shocks are amplified within the internal firm network.

Given the nature of our data, it appears plausible that our estimates are driven by higher order effects, i.e. losses incurred by the specific structure of economic dependencies within the network (Wenz and Levermann 2016). Stable, long-term ownership can possibly capture relationships that are of important value to the network. For instance, Barrot and Sauvagnat (2016) show that shock propagation between supplier and customer firms is substantially stronger and more significant if the supplier produces specific inputs that are hard to replace. The divergence between first and higher order effect sizes might also be related with subsidiary firms being more resilient to shocks as the bulk of the impact is absorbed by the network. Giroud and Mueller (2019) demonstrate that subsidiaries have smaller employment elasticities with respect to local shocks than independent companies. However, more research on the interplay between shock exposure and structural business group features is needed.

The strong impacts of extreme heat on and within business groups are in line with recent findings on economic outcomes. For instance, studies demonstrated that average global incomes could decrease by up to 23% by 2100 (Burke et al. 2015) or that losses in Chinese manufacturing could incur yearly GDP losses of around 5% by 2050 (Zhang et al. 2018). Wenz and Levermann (2016) find that inter-sectoral trade can greatly amplify heat-induced losses. While we cannot provide representative aggregate estimates with our dataset, the firm-based estimates suggest that the effects are economically important. Given the overlap in current and future weather distributions, the results can provide us with a useful estimate of potential medium-run impacts of climate change induced heat stress.

An important empirical question is to what degree the effects we obtain for the medium-run persist into the long-run. Although firms that operate in relatively hot climates had sufficient time to adapt, the magnitude of the coefficients is sizeable which suggests that effects may continue into the future. However, no clear consensus has emerged so far on adaptation with some studies detecting limited potentials and other studies indicating the opposite (Behrer and Park 2018, Pankratz and Schiller 2021). More research on how to alleviate the impacts of extreme temperature, particularly using longer time horizons, is needed (Kalkuhl and Wenz 2020).

From a policy perspective, it is important to understand if local shocks can be contained and prevented from spreading to the regional and global level. In terms of adaptation, one would expect business groups to move their subsidiary locations or to integrate new, less exposed firms into their networks. In fact, Pankratz and Schiller (2021) find evidence that customer firms are more likely to replace suppliers if these suppliers climate risk exposure is higher than expected. However, the empirical literature on network production also demonstrates that switching costs can be substantial and thus impede adaptation to economic shocks at least in the short run (Antràs and Yeaple 2013, Bernard and Moxnes 2018). In line with recent evidence (Barrot and Sauvagnat 2016), our results suggest that the importance of switching costs may be high when it comes to specific long-standing relationships. More research on the persistence of effects and the importance of switching costs in the long run as well on how to alleviate these impacts is needed.

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