Supply chain transmission of climate-related physical risks*

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Abstract

How do climate anomalies affect GDP growth, and how do trade connections help understand this impact? We address these questions with data on fluctuations in temperature and precipitation coupled with supply chain linkages between municipalities in Brazil. GDP growth falls concomittantly with dry wells and to a lower extent, also wet spells. This occurs even when the climate anomaly is moderate. This impact is sufficiently material to transmit across supply chain connections to municipalities with customer and supplier firms. We also examine the major economic sectors separately and find that agricultural and manufacturing GDP growth rates are more sensitive to supply chain transmission of physical shocks than services GDP. This suggests that the local economic mix can be a potentially important driver of effect heterogeneity.

1 Introduction

The macroeconomic impacts of physical shocks and their amplification mechanisms continue to be an important knowledge gap (Battiston, Dafermos, and Monasterolo (2021)). This work documents the importance of supply chains to paint a more complete picture of physical risks from climate change. Our analyses concentrate on the transmission of physical shock across Brazilian municipalities directly connected to each other by trade. Using a unique administrative dataset, we explore the economic effects of local climate anomalies of different intensities in aggregate and across sectors. Next, we study how these economic impacts spread through supply chains beyond any local effect. Importantly, our estimates benefit from Brazil's continental size to disentangle the effects of simultaneous shocks occurring locally and in municipalities where supplier or customer firms are located.

Our data and methodology afford multiple dimensions of analyses. For example, the climate anomalies can relate to either wet or dry spells, and have different levels of intensity. In terms of location, the anomalies are measured for each municipality, but in our analyses they can also enter regressions as suppliers and/or customers to each other. Further, each municipality pair is identified as being a (geographically) "distant" link or not, where it is assumed that the distant ones do not share the same physical anomalies because of the distance. Finally, the economic outcome of interest is GDP growth at each municipality, as a whole or divided into agriculture, manufacturing or services sectors.

Using similar measurements of climate anomalies as in the scientific literature, we show that adverse climate anomalies of both moderate and intense magnitude influence local economic outcomes. And in turn, these

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local shocks impact other regions' economic growth, even hundreds of kilometers away, due to supply chain linkages. But the effect of local and supply chain-transmitted climate shocks is heterogeneous, depending on the different mix of economic activity of each municipality: agriculture and manufacturing GDP growth rates are more sensitive to supply chain transmissions whereas services GDP growth is, on average, insulated from these shocks.

To familiarise readers with our data, we first exploit variation in climate anomalies over time and across municipalities to measure their effect on local economic growth. Controlling for unobserved time and municipality effects, past GDP growth and past climatic conditions, local annual GDP growth falls markedly after climate anomalies. Periods of lower precipitation by one standard deviation (s.d.) or more of the historical average (a dry spell) reduces growth on average by more than 1 percentage point, with a stronger significance result. Breaking down the anomalies into a "moderate" and an "intense" group, where the former is defined as between one and two local s.d. and the latter as those anomalies whose absolute value is over two local s.d., we find that moderate shocks explain the bulk of the dry spell results.

Given the salience of these local effects, we use a network of firm interbank payments across Brazil to estimate whether supply chains contribute to spreading local physical shocks. Controlling for local anomalies and climate, a higher share of incoming payments from firm customers in municipalities experiencing day spells has a negative lagged effect on GDP of more than 1 p.p. for all municipalities; the effect is lager at 2 p.p. of contemporaneous GDP for remote municipalities. Both moderate and intense dry spells os customer municipalities contribute to this effect. For suppliers, the physical shock that spreads in the supply chain is that of higher precipitation: wet spells in supplier municipalities cause 0.9 p.p. lower GDP growth one year later.

Breaking down the impact measures by economic sector, we find that agricultural GDP growth tends to suffer more from local climate anomalies compared to manufacturing and services GDP. And the supply chain transmission of shocks is also different: agricultural GDP is lower when customer municipalities experience dry shocks, with effects hovering 4 p.p if all customers had such a physical shock. Conversely, manufacturing GDP growth, which is also impacted by local shocks albeit at a smaller scale, decreases after a dry spell at supplier municipalities. Services GDP, in contrast, is lower when a municipality faces a local physical risk but does not respond to customer or supplier climate shocks. These sectoral supply chain results consider only remote municipality pairs, pointing to the strength of supply chain transmission of physical shocks.

A long literature explores the economic effect of physical risks or the broader set of natural disasters (including geological events). Deryugina (2017) documents the fiscal effects of hurricanes even considering relief measures. In a study of the 1950's drought in the US, Rajan and Ramcharan (2023) show that ex ante credit availability had a sizeable impact on the long-run effects of the drought through changing the ability of affected towns to adapt to the circumstances through investment and innovation. A crucial distinction is on the short-vs long-run effects of physical risks, such as in Hornbeck (2012). Kim, Matthes, and Phan (2022) use a smooth transition vector autoregression (pioneered by Auerbach and Gorodnichenko (2012)) applied to United States data and find that climate-related physical risks have a substantial effect on macroeconomic variables (industrial production, consumption, unemployment and inflation). Parker (2018) finds that climate disasters impact inflation. Barrot and Sauvagnat (2016) use natural disasters in the US to document large effects on customer firms when their suppliers are disrupted, in a way that is consistent with specificity of their input to the production chain. Boehm, Flaaen, and Pandalai-Nayar (2019) study the global sectoral connections in light of the Japanese earthquake and Feng, Li, and Wang (2023) show that international trade connections explains cross-border spillovers of climate-related physical risks. More broadly, Acemoglu et al. (2012) show how sectoral shocks and their second-order effect can explain aggregate outcomes.

Our findings contribute in three main ways to the strands of literature mentioned above on the economic fallout of physical risks and on the transmission of shocks through supply chain linkages. First, we document

economically relevant impacts of physical shocks also for climate anomalies that are not extreme or disastrous. This can raise awareness of the importance of those shocks to climate-related physical risks, until now almost exclusively focused on extreme events in the literature. In addition, results from moderate shocks can be more easily considered as externally valid compared to findings from more disaster-focused studies, which shed light on important economic questions but in some cases may be applicable only in similarly extreme situations. The second contribution is the strong evidence on how supply chain connections transmit climate economic shocks. Since these effects are measured after controlling for time, municipality and a set of geographic characteristics, they can be interpreted as occurring above and beyond effects of climate anomalies on prices or other incentives that are not related to the trade linkages. Our third contribution relates to uncovering important aspects that drive heterogeneity in responses to local and remote climate shocks, in this case through the mix of local economic activity between the agricultural, manufacturing and services sectors.

Brazil is a good laboratory for studying the economic impact of climate shocks. Its continental area, geographical diversity, heterogeneous weather patterns as well as its vast biodiversity, result in variations in the exposure to climate-related events (Pörtner et al. (2022) presents a detailed description). At the same time, Brazil is a middle-income country with municipalities in different levels of socio-economic development, all of them subjected to the same federal legal and monetary framework that allows for comparability between its regions. Importantly, as documented in Figure 1, most catastrophes in Brazil are related to climate, rather than from geological disasters.

Supply chain are but one form of transmission of local shocks to other localities. Other long-recognised channels include changes in prices (Hayek (1945), Flori, Pammolli, and Spelta (2021)), common banking links (Peek and Rosengren (1997), Fender and McGuire (2010), Cortés and Strahan (2017), Ivanov, Macchiavelli, and Santos (2022)), tourism flows (Anastasia Arabadzhyan and León (2021)), etc. And supply chains of course do not transmit only climate-related shocks: a long literature documents how trade links spread other natural disasters and even ad hoc trade events (Lafrogne-Joussier, Martin, and Mejean (2023)). Still, we argue that climate-related physical risks occurring below the threshold of disaster are not only significantly at the local level but also through trade links.

The rest of the paper is organized as follows. Section 2 describes the data and offers some background information on changes in average temperature and precipitation experienced by Brazilian municipalities in recent decades and presents the network of linkages among firms located in different municipalities. Section 3 analyse the local impact of climate anomalies, and Section 4 elaborates on those results to document the transmission of shocks through trade linkages. Section 5 breaks down the economic impacts into different broad sectors. Then Section 7 discusses in more detail the limitations of the data and empirical strategy, while Section 8 connects the dots and concludes.

2 Data

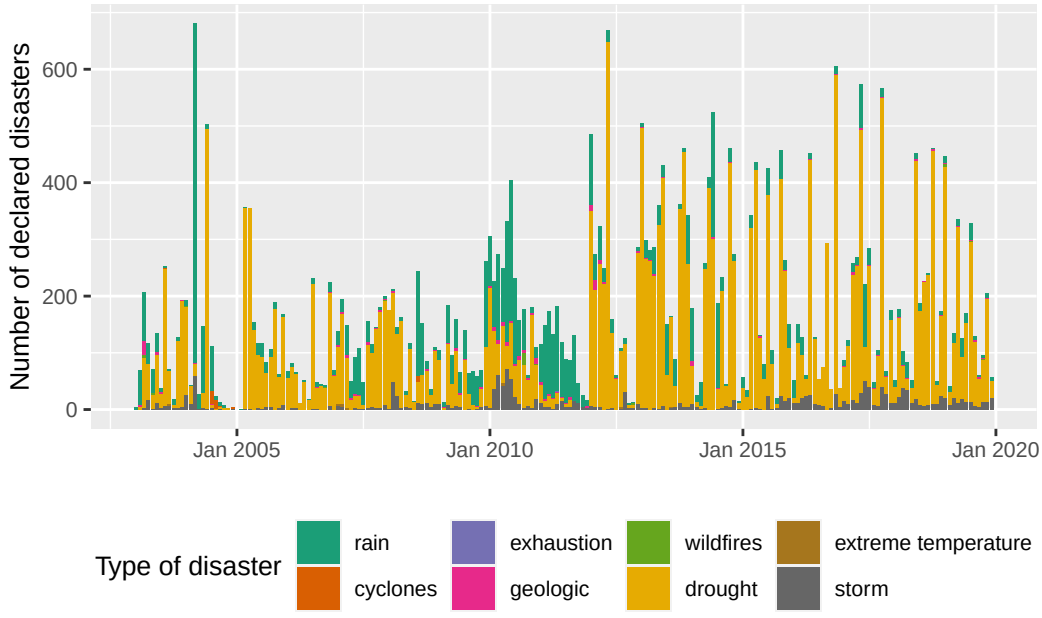
We combine multiple publicly-available climate and economic data at the municipal level with confidential Banco Central do Brasil (BCB) payments data. The primary features of these data are the richness of the data including firm economic sector and the disaggregated geographical level information, and the use of multiple complementary measures of weather anomalies that do not depend on individually identified large scale disasters. The research period spans from 2000 (local shocks) or 2012 (with supply chain data) to end-2019, a sufficiently long period that encompasses different economic policies and business cycle dynamics but avoids the turbulent Covid-19 pandemic period.

2.1 Climate data

Similar to the scientific literature on climate anomalies, our measure of climate anomalies comes from divergences in precipitation in a given location from its historical distribution. In particular, we use municipality-

level precipitation and temperature readings since 1961 to calculate the *Standardized Precipitation Evapotranspiration Index* (SPEI) (Vicente-Serrano, Beguería, and López-Moreno 2010). This indicator measures the divergence between actual precipitation in a given location and the expected values for that location in a given time window given the precipitation history, adjusted by temperature. The SPEI values are standardised to be measured in standard deviations (s.d.) for each location. This makes local SPEI indices comparable across locations and time. Positive readings indicate wetter climates than the historical average for a location, and conversely negative readings point to occurrences of droughts. This indicator is the basis for the physical shocks in this study due to the prevalence of this type of precipitation-related climate anomaly across Brazil (Figure 1).

Figure 1: Declared environmental disasters in Brazil



The SPEI measured at each time window reflects different physical implications of climate anomalies. For example, one-year SPEI is more informative about the effect of drought on soil humidity and river volumes, while five-year SPEI levels indicate more structural implications, such as on underground water reserve levels. Our preferred measure of physical shock is the one-year SPEI. A year-long deviation can be sufficiently material to overwhelm short-term resilience measures (such as input stocks in manufacturing firms) while not long-term enough to reshape how supply chains are structured. For example, abnormally high one-year SPEIs could indicate cases of excessive rain that leads to urban flooding, causing both loss of life and wealth (often also affecting poorer households' goods) as well as logistic obstacles to commerce.[1] In addition, a one-year shock horizon maps well with the annual frequency of the municipal GDP data.[2]

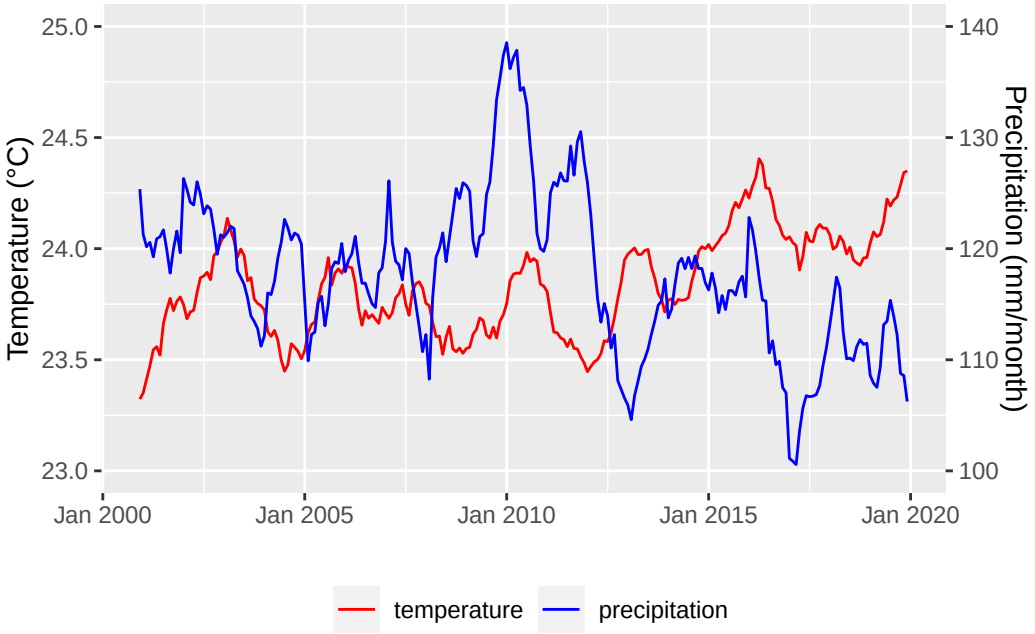
[1]One of various examples from local news is about the damages to trucks hauling goods to and from a São Paulo warehouse, at (in Portuguese): https://valor.globo.com/agronegocios/noticia/2020/02/10/chuva-em-sp-leva-ceagesp-a-paralisar-atividades.ghtml.

[2]Throughout the paper, the main results are estimated with SPEI. But quantitative analyses with the related indicator *Standardized Precipitation Index* (SPI) (McKee et al. (1993), Edwards and McKee (1997), Guttman (1999)) are also available in the Annex. Conceptually, both the SPEI and SPI are different ways of calculating the deviations of precipitation from the long-term average for that same location and time period in the year, with these differences standardised according to the same distribution. The main difference between the SPEI and SPI is that the former relates only to precipitation, while the latter also corrects for changes in the temperature of a given location to better reflect the phenomenon of evapotranspiration,

The historical weather data for the SPEI are taken from the widely-used Climatic Research Unit gridded Time Series (CRU TS) monthly dataset, version 4 (Harris et al. (2020)). This is a climate dataset on a grid with a resolution of 0.5° x 0.5° in latitude and longitude that consists of weather variables such as precipitation, temperature, diurnal temperature range, cloud cover, wind speed, and others. We use monthly precipitation and average daily mean temperature to calculate the SPEI at the municipality level using the SPEI R package (Beguería et al. 2014), with the gamma distribution calibrated for each specific time horizon.[3]

Another interesting empirical feature that Brazil offers for the study of physical risks comes from the wide fluctuations in temperature and precipitation conditions observed during the research period. This is best seen in Figure 2, which portrays the 12-month rolling averages of the national unweighed mean from municipal readings of temperature and precipitation. Temperature levels have remained broadly below 24°C up until 2015, and have been consistently above that level since. And the precipitation level has swung widely to a peak in 2010, gradually falling since to reach levels that were not seen in the two decades before.

Figure 2: Average 12-month temperature and precipitation levels in Brazil



Our definition of "physical shock" is statistical: the positive and negative SPEI values of more than one s.d. identify the "anomalous" episodes. Positive SPEI anomalies are generally referred to as "wet spells"; conversely, negative SPEI anomalies are "dry spells" throughout. This definition benefits from an intuitive understanding that anomalies are events tending towards the tails of distributions, and allows a natural quantitative comparison of the shocks. To simplify the analyses, we consider all anomalies of more than two s.d. (or less than negative two s.d.) to be "intense", while the ones between one and two s.d. are called "moderate".

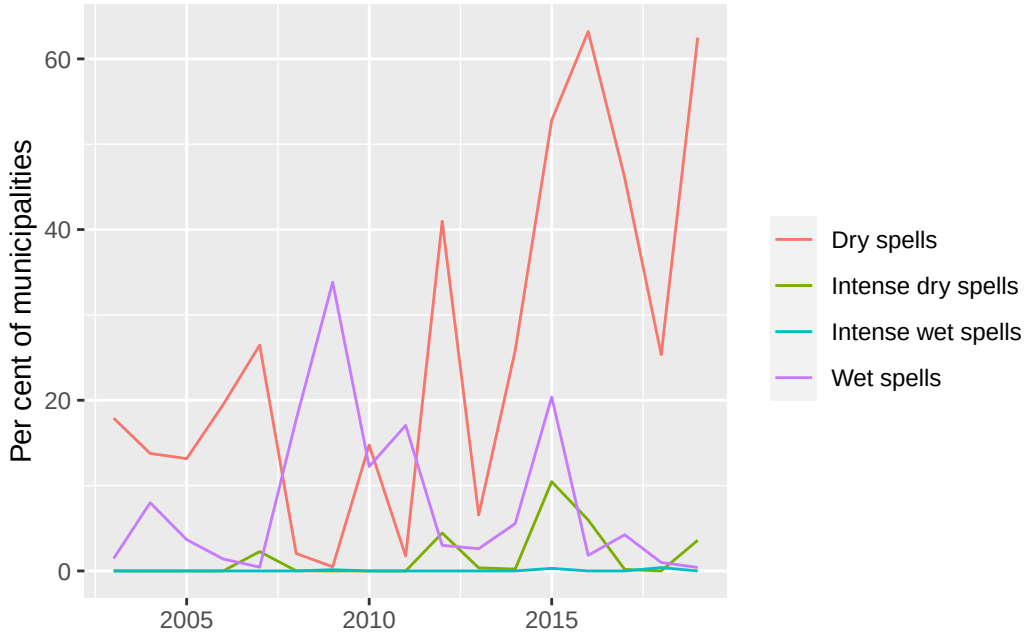
Figure 3 shows the evolution of the climate anomalies identified this way. Note the virtual absence of intense positive shocks. For this reason, the empirical specifications below do not include this particular type of

which is important for many physical phenomena such as water absorption by the soil or its use by plants. These sets of results are broadly the same.

[3]All past observations in a time horizon carry the same weight (ie, the SPEI uses a rectangular kernel).

anomalies.

Figure 3: Evolution of climate anomalies



2.2 Supply chain data

The supply chain network is based on confidential BCB data on electronic funds transfers between firms' bank accounts at different banks.[4] This payment modality has no upper ceiling and settles on the same day, reasons for which it is widely used for interfirm payment. Correspondingly, these payments represent 42% of all values according to BCB data,[5] the largest value share in the payments system within our period of analysis. Notably, this share is stable since before the pandemic, even with the advent of the popular instant payments system Pix (Duarte et al. 2022)[6]. This suggests it is an important payment for firms.

Importantly in our case, these electronic fund transfers help differentiate trade-related payments: other business-to-business payments such as utilities companies, are often settled via payment stubs, which use a different payments rail and are not captured in this data. The same firm-to-firm payments data have been used in other studies as a proxy for the supply chain network (eg Martins, Schiozer, and Linardi (2023)) and also by the BCB in its oversight activities (Banco Central do Brasil (2015)). Figure 4 presents the total amounts considered in our study.

Other works in the literature identify trade linkages with invoices (eg, Acevedo et al. (2023)) or regulatory filings by publicly-traded companies (eg, Qiu, Shin, and Zhang (2023)). Using payments data to proxy for supply chains, as done in this paper, has advantages and disadvantages. Payments identify exactly firms that are customers and suppliers to each other, even when these trade relationships are informal and thus are not documented in invoices. Payments also expand the universe of firms for which there is supply chain

[4]Transfers between bank accounts in the same bank are settled internally in the bank's systems ("book transfer") and therefore do not go through the BCB payments system.

[5]Available at https://www.bcb.gov.br/estatisticas/spbadendos/.

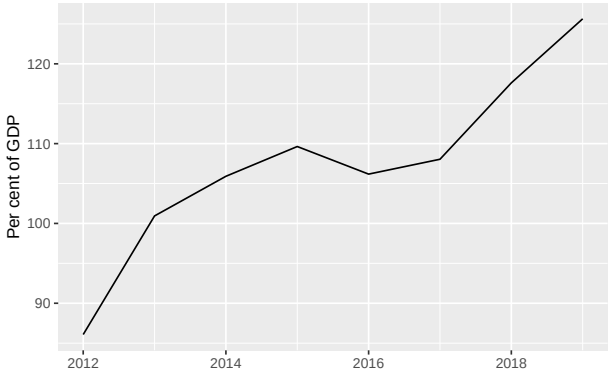
[6]Available at https://www.bcb.gov.br/estabilidadefinanceira/estatisticaspix/.

data beyond the typically large firms that are in some cases required to disclose public information. Another advantage is that the actual amounts are, by definition, observed.

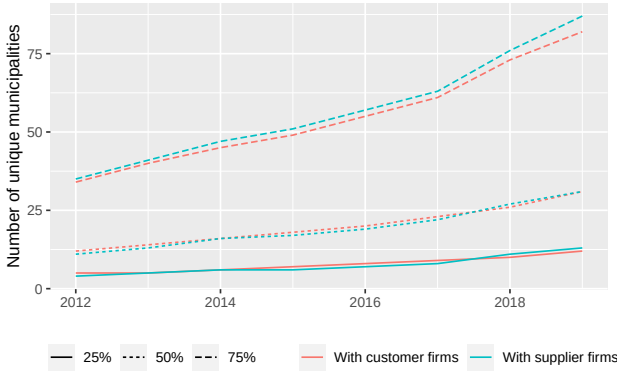
However, there are important limitations in how much the payments data we use can identify supply chain relationships. First, we cannot measure the whole supply chain network: as mentioned above these payments only consider electronic transfers between accounts in different banks, since intrabank transfers are settled internally by the bank via book transfer. Cash or credit card payments are also not included, although typically those would relate to very small firms or mundane low-ticket purchases instead of actual production inputs. Transactions settled outside of Brazil, such as foreign trade, are also not considered. This means that supply chain identification might be suboptimal, especially in smaller municipalities where only one or two banks have active presence (generally the large, government-owned banks), when for some reason firms in the same sector tend to converge in the same bank (Paravisini, Rappoport, and Schnabl (2023)). Another potential limitation is that electronic funds transfers correspond to the actual payment, not the sales process: in other words, firms that end up not paying their trade debts after they are due are not reflected in our data, even if the original purchase of goods or services from another firm created economic demand along its supply chain. Finally, the sample is constructed by clipping lower-value payments to constraint the dataset size and facilitate analyses. Only those payments with a minimum bilateral interfirm relationship of R$ 10,000 each quarter (around $2,300 as of November 2023) are present in the data.

Figure 4: Network metrics

(a) Electronic payment transfers between firms in Brazil



(b) Evolution of network connections



2.3 Economic and geographic variables

The municipality-level economic and geographic variables come from the Brazilian statistical institute (IBGE). We obtain annual municipal GDP (in total and divided by broad economic sectors), as well as latitude and longitude coordinates of each municipality. In addition, the data mentions whether a municipality is officially in the Legal Amazon region or the Semi-Arid region, two multi-State regions in Brazil that share each common climatic, geographic and socio-economic characteristics. The municipal GDP growth numbers are summarised in Table 1.

Table 1: Municipal GDP growth in Brazil

	GDP		GDP agriculture		GDP manufacturing		GDP services	
Year	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2012	0.092	0.147	-0.041	0.326	0.094	0.331	0.144	0.131
2013	0.136	0.157	0.191	0.326	0.049	0.359	0.136	0.125
2014	0.092	0.138	0.069	0.259	0.112	0.346	0.124	0.142
2015	0.065	0.137	0.031	0.234	0.053	0.356	0.070	0.118
2016	0.082	0.144	0.144	0.275	0.036	0.350	0.081	0.130
2017	0.051	0.131	-0.025	0.322	0.038	0.300	0.065	0.124
2018	0.044	0.125	-0.021	0.236	0.044	0.316	0.060	0.118
2019	0.051	0.107	0.017	0.230	0.068	0.274	0.058	0.107

3 The effect on local economic activity

In this section, we lay out our basic empirical strategy for the analysis of physical shocks and their effects on GDP growth These local impacts act as a natural benchmark for the subsequent results.

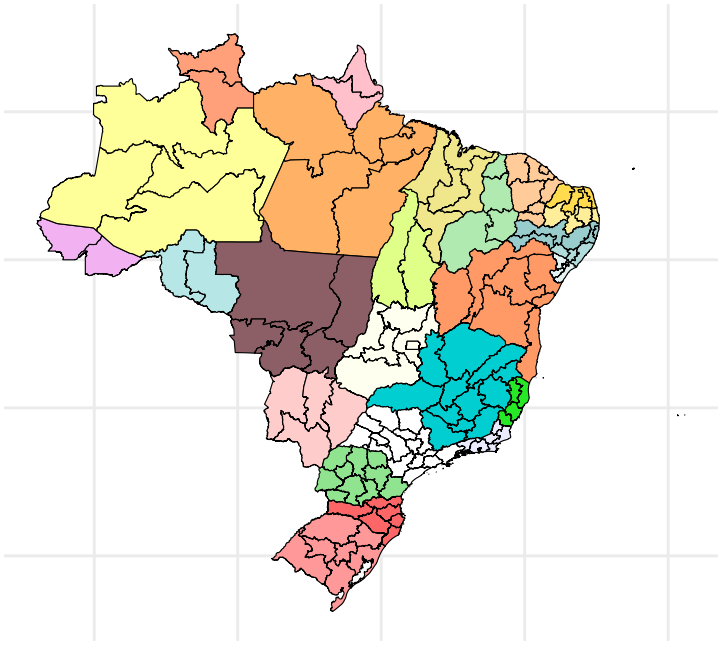
We begin by estimating the effects of temperature and precipitation anomalies as captured by SPEI on aggregated outcomes at the municipality-year level. Our core model used to estimate the effects from local climate anomalies is Equation 1:

$$y_{i,t} = \theta y_{i,t-1} + \alpha_i + \gamma_t + \iota \kappa_{i,t-1} + \sum_k \beta^k_{\text{Local}} \eta^k_{i,t} + \epsilon_{i,t}, \tag{1}$$

where $y_{i,t}$ is the yearly GDP growth of the municipality i in year t, α_i denotes municipality fixed effects to absorb municipality-specific time-invariant characteristics, and γ_t denotes year fixed effects to control for year-specific characteristics/shocks common to all locations. $\kappa_{i,t-1}$ is the vector of existing climatic conditions (temperature and precipitation) at municipality i in the previous year; and ι is the adaptation coefficient. $\eta^k_{i,t}$ are measurements of climate anomalies with $k \in \{\text{positive}, \text{negative}\}$ is the type of climate anomaly, representing whether the shock is positive (wet spells) or negative (dry periods). Specifically, $\eta^k_{i,t}$ are defined in this paper as 1 if the one-year SPEI is higher or lower than ± 1 s.d. (depending on k), and zero otherwise. $\epsilon_{i,t}$ is the error term, with a covariance matrix clustered at the mesoregion level (see Figure 5).[7]

[7]The Federal District mesoregion only has one municipality, Brasília. We merge it into the East Goiás mesoregion, avoiding a single-municipality cluster.

Figure 5: Brazil mesoregions, coloured by Brazilian State



The coefficients of interest are β^k_{Local}, which measure the effect of the different weather anomalies on local economy. Equation 1 can be interpreted as a simple stochastic growth model (Brock and Mirman (1972)). Von Peter, Von Dahlen, and Saxena (2012) also uses a similar type of stochastic growth model to estimate the macroeconomic long-term costs of natural disasters, albeit with more lags.

The estimates of Equation 1 are in Table 2. There is a statistically and economically significant effect of lower precipitation on economic growth, similar to other studies (Mohaddes et al. 2023). Both wet and negative spells are associated with lower economic growth. Wet spells are associated with circa half a percentage point lower growth, while negative precipitation shocks contemporaneously lower annual GDP growth by more than 1 percentage point on average with more statistical significance. These results are on top of constant municipality or period effects, as well as municipality-specific lagged climate conditions. These estimates suggest that climate anomalies are associated with sizeable output losses of local economies.

Table 2: Influence of local abnormal precipitation on GDP

Dependent Variable:	GDP growth	
Model:	(1)	(2)
Variables		
SPEI(1y) > 1 s.d.	-0.0051*	-0.0059*
	(0.0030)	(0.0030)
SPEI(1y) < -1 s.d.	-0.0173***	-0.0137***
	(0.0028)	(0.0026)
Avg. prec. (t-1)		0.0003*
		(0.0002)
Avg. temp. (t-1)		0.0287**
		(0.0120)
GDP growth (t-1)	-0.1859***	-0.1841***
	(0.0146)	(0.0142)
Fixed-effects		
Municipality	Yes	Yes
Year	Yes	Yes
Fit statistics		
Observations	88,931	88,931
R^2	0.11958	0.12165
Within R^2	0.03779	0.04005

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Breaking down physical shocks into the ones that are moderate and the more intense ones highlights the importance of moderate shocks to economic outcomes. As seen in Table 3, the effects observed in Table 2 can be attributed mostly to the moderate portion of the shocks. Moderate day spells lower GDP growth by more than one percentage point. And while more intense shocks have a statistically significant impact that is larger in magnitude than that of moderate shocks, this effect dilutes when climatic conditions are considered. While intense shocks capture headlines and are also the identifying assumption in part of the physical risks literature, these results suggest.

In the following analyses, the climate anomalies will not be broken down into moderate and more intense shocks as done in Table 3 for purposes of simplicity (given there are already many dimensions to be explored). However, their strong local effect can be assumed to be one of the potential shocks that can be transmitted to other municipalities via supply chain linkages.

Table 3: Influence of local moderate and intense abnormal precipitation on GDP

Dependent Variable:	GDP growth	
Model:	(1)	(2)
Variables		
Mod. pos. SPEI(1y)	0.0213	0.0140
	(0.0177)	(0.0173)
Mod. neg. SPEI(1y)	-0.0166***	-0.0132***
	(0.0028)	(0.0025)
Int. neg. SPEI(1y)	-0.0213***	-0.0135*
	(0.0065)	(0.0071)
Local prec. lag		Yes
Local temp. lag		Yes
Local GDP lag	Yes	Yes
Fixed-effects		
Municipality	Yes	Yes
Year	Yes	Yes
Fit statistics		
Observations	88,931	88,931
R^2	0.11952	0.12154
Within R^2	0.03773	0.03993

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

4 Supply chain transmission of climate shocks

The significance of local physical shocks for economic growth raises the question on potential spillover to other regions connected by trade. In this section, we study the transmission of physical shocks over the supply chain network. Compared to the previous section, we now combine the municipality climate and GDP data with the network of municipalities connected by payments between firms. We obtain an estimate of the macroeconomic impact of the weather shock beyond the impact on municipalities directly exposed to the shock by taking these propagation effects into account. Note that the regressions from this section onward have less data points because the supply chain dataset starts in 2012.

We extend Equation 1 to include shocks from other municipalities where supplier and customer firms are located in Equation 2 below:

$$y_{i,t} = \alpha_i + \gamma_t + \iota\kappa_{i,t-1} + \beta^{\text{Local}}\eta^k_{i,t} + \sum_k \sum_j \beta^k_{\text{Customers}}\omega_{i,j,t}\eta^k_{j,t} + \sum_k \sum_h \beta^k_{\text{Suppliers}}\rho_{i,h,t}\eta^k_{h,t} + \epsilon_{i,t}, \quad (2)$$

with

$$\omega_{i,j,t} \geq 0, \sum_j \omega_{i,j,t} \leq 1 \text{ and } \rho_{i,j,t} \geq 0, \sum_j \rho_{i,j,t} \leq 1,$$

where $\omega_{i,j,t}$ and $\rho_{i,j,t}$ are the shares that municipality j represent on i's total customers and suppliers,

respectively, including in this share the firms that buy and sell to other firms also in municipality i. Hence, these weights don't necessarily sum up to unit. The coefficients of interest are $\beta^k_{\text{Customers}}$ and $\beta^k_{\text{Suppliers}}$.

4.1 Shocks in customer municipalities

First, we examine the role of climate anomalies in municipalities where customer firms are located. Table 4 presents the results for regression of local GDP growth on the share of incoming payments from other municipalities that experience climate anomalies in the same year or in the previous one.

Table 4: Influence of local and customer precipitation on local GDP

Dependent Variable:	GDP growth		
Model:	(1)	(2)	(3)
Variables			
SPEI(1y) > 1 s.d.	-0.0187***	-0.0255***	-0.0228***
	(0.0060)	(0.0065)	(0.0064)
SPEI(1y) < -1 s.d.	-0.0096**	-0.0075	-0.0073
	(0.0037)	(0.0047)	(0.0046)
Inpmts. SPEI(1y) > 1 s.d.	-0.0077		-0.0164
	(0.0113)		(0.0182)
Inpmts. SPEI(1y) < -1 s.d.	-0.0056		-0.0012
	(0.0043)		(0.0048)
Inpmts. SPEI(1y) > 1 s.d. (t-1)		-0.0018	-0.0015
		(0.0113)	(0.0118)
Inpmts. SPEI(1y) < -1 s.d. (t-1)		-0.0103*	-0.0112*
		(0.0057)	(0.0063)
Local prec. lag	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes
Fixed-effects			
Municipality	Yes	Yes	Yes
Year	Yes	Yes	Yes
Fit statistics			
Observations	42,703	37,233	36,799
R^2	0.16965	0.20451	0.20416
Within R^2	0.06181	0.07491	0.07533

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Consistent with Table 3, there is evidence that dry spells in municipalities with customer firms lower GDP growth, even after local climate anomalies and other conditions are considered. Interestingly, this transmission takes time: contemporaneous physical shock in customer municipalities do not impact local growth, only when customers were impacted in the previous year.

It is possible that municipality pairs experience the same climate anomalies if they are geographically close. To reduce this effect, we present in Table 5 the results only for connected municipalities that are

more distant than the median distance between Brazilian municipalities, which is approximately 572.9 km.[8] Municipalities far apart for more than 572.9 km are likely to not share the same climate or weather patterns, assuaging concerns about commonality of climate anomalies being the main driver of the results.

The results point to a strong effect of customer dry shocks: if all sales of a municipality went to customers in remote municipalities suffering dry spells, GDP growth would be more than 2 percentage points lower. While the magnitude of the coefficient hints at the strength of this relationship, it is important to consider that the subset of remote municipalities comprises a smaller share of sales than the whole population of municipalities. Another interesting point to raise is that these remote shocks, which are more likely to affect a municipality mostly through trade connections, impact GDP growth contemporaneously.

Table 5: Influence of local and remote customer abnormal precipitation on local GDP

Dependent Variable:	GDP growth		
Model:	(1)	(2)	(3)
Variables			
SPEI(1y) > 1 s.d.	-0.0188***	-0.0243***	-0.0230***
	(0.0052)	(0.0061)	(0.0061)
SPEI(1y) < -1 s.d.	-0.0107***	-0.0080*	-0.0082*
	(0.0037)	(0.0046)	(0.0046)
Inpmts. remote SPEI(1y) > 1 s.d.	0.0095		0.0366*
	(0.0130)		(0.0202)
Inpmts. remote SPEI(1y) < -1 s.d.	-0.0183*		-0.0232**
	(0.0098)		(0.0114)
Inpmts. remote SPEI(1y) > 1 s.d. (t-1)		0.0043	0.0163
		(0.0152)	(0.0157)
Inpmts. remote SPEI(1y) < -1 s.d. (t-1)		-0.0015	0.0033
		(0.0100)	(0.0097)
Local prec. lag	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes
Fixed-effects			
Municipality	Yes	Yes	Yes
Year	Yes	Yes	Yes
Fit statistics			
Observations	38,233	33,058	31,955
R^2	0.18006	0.21315	0.21421
Within R^2	0.05742	0.07294	0.07426

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

As for local shocks, evidence suggests that moderate dry spells in customer municipalities can also impact growth. Both columns of Table 6 break down transmissions of dry spells from remote customers into moderate and intense shocks, with the first column examining contemporaneous and the second one, lagged

[8]This is comparable to the distance between Basel and Amsterdam, San Francisco and Los Angeles, Luanda and Kinshasa or Tokyo and Aomori as the crow flies.

shocks. Moderate and intense dry spells in remote customer municipalities depress GDP growth, helping to explain the results in Table 5.

Table 6: Influence of local and remote customer abnormal precipitation on local GDP by intensity

Dependent Variable:	GDP growth	
Model:	(1)	(2)
Variables		
SPEI(1y) > 1 s.d.	-0.0190***	-0.0243***
	(0.0052)	(0.0061)
SPEI(1y) < -1 s.d.	-0.0106***	-0.0080*
	(0.0037)	(0.0046)
Mod. neg. inpmts. remote SPEI(1y)	-0.0182*	
	(0.0094)	
Int. neg. inpmts. remote SPEI(1y)	-0.0489*	
	(0.0278)	
Mod. neg. inpmts. remote SPEI(1y) (t-1)		-0.0016
		(0.0103)
Int. neg. inpmts. remote SPEI(1y) (t-1)		-0.0126
		(0.0255)
Local prec. lag	Yes	Yes
Local temp. lag	Yes	Yes
Local GDP lag	Yes	Yes
Fixed-effects		
Municipality	Yes	Yes
Year	Yes	Yes
Fit statistics		
Observations	38,233	33,058
R^2	0.18007	0.21315
Within R^2	0.05744	0.07294

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

In short, evidence suggests that dry spells in municipalities with customer firms affect local GDP growth, even after considering the local climatic situation. This effect is due, in part, to moderate shocks, even in remote municipalities.

4.2 Shocks in supplier municipalities

In this section, we investigate the potential effect of climate shocks occurring in municipalities with supplier firms. Table 7 shows the results for the regression of municipalities' GDP growth rates on the share of outgoing payments to other municipalities that experienced climate anomalies.

In contrast to impact from shocks on customer municipalities, spillovers from supplier municipalities are due to wet spells. For the population of all possible municipalities, this effect plays out with a lag.

Table 7: Influence of local and supplier precipitation on local GDP

Dependent Variable:	GDP growth		
Model:	(1)	(2)	(3)
Variables			
SPEI(1y) > 1 s.d.	-0.0202***	-0.0266***	-0.0261***
	(0.0057)	(0.0063)	(0.0064)
SPEI(1y) < -1 s.d.	-0.0103***	-0.0072	-0.0070
	(0.0037)	(0.0047)	(0.0047)
Outpmts. SPEI(1y) > 1 s.d.	-0.0005		0.0003
	(0.0027)		(0.0016)
Outpmts. SPEI(1y) < -1 s.d.	-0.0010		-0.0009
	(0.0009)		(0.0010)
Outpmts. SPEI(1y) > 1 s.d. (t-1)		-0.0088***	-0.0089***
		(0.0023)	(0.0023)
Outpmts. SPEI(1y) < -1 s.d. (t-1)		0.0005	0.0003
		(0.0006)	(0.0005)
Local prec. lag	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes
Fixed-effects			
Municipality	Yes	Yes	Yes
Year	Yes	Yes	Yes
Fit statistics			
Observations	42,747	37,238	36,714
R^2	0.17059	0.20748	0.20875
Within R^2	0.06162	0.07791	0.07811

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

As a robustness check, in Table 8 we present the results only for remote supplier municipalities. These results confirm the previous findings that lagged wetter years in supplier municipalities significantly impact local GDP growth.

Table 8: Influence of local and remote supplier abnormal precipitation on local GDP

Dependent Variable:	GDP growth		
Model:	(1)	(2)	(3)
Variables			
SPEI(1y) > 1 s.d.	-0.0199***	-0.0245***	-0.0252***
	(0.0058)	(0.0065)	(0.0065)
SPEI(1y) < -1 s.d.	-0.0099**	-0.0069	-0.0073
	(0.0038)	(0.0046)	(0.0047)
Outpmts. remote SPEI(1y) > 1 s.d.	-0.0008		0.0029
	(0.0030)		(0.0026)
Outpmts. remote SPEI(1y) < -1 s.d.	-0.0021		-0.0024
	(0.0016)		(0.0021)
Outpmts. remote SPEI(1y) > 1 s.d. (t-1)		-0.0098***	-0.0099***
		(0.0029)	(0.0029)
Outpmts. remote SPEI(1y) < -1 s.d. (t-1)		0.0005	0.0003
		(0.0010)	(0.0009)
Local prec. lag	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes
Fixed-effects			
Municipality	Yes	Yes	Yes
Year	Yes	Yes	Yes
Fit statistics			
Observations	37,108	32,015	30,275
R^2	0.18056	0.21518	0.21879
Within R^2	0.05933	0.07306	0.07583

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

To summarise, wet spells in municipalities with supplier firms also impact negatively local GDP growth, albeit with a lag. This result is observed also when only remote municipality pairs are considered. Due to the virtual absence in our data of intense wet spells in our sample, we attribute these results to moderate spells.

5 Sectoral impacts from local and supply chain shocks

Physical shocks span a wide variety of potential threats to economic activity, across all sectors. Impacts of local climate anomalies on agriculture appear to be the most intuitive given the strong relationship between crop or husbandry yields and climate variables. However, other activities such as manufacturing or services may also be impacted due to physical damages to structures or to extreme heat, for example, or supply chain disruptions. In this section we investigate whether local and supply chain-transmitted weather shocks impact economic sectors differently. To do this, we focus on sectoral GDP growth in three sectors: agriculture, manufacturing and services.

Table 9: Influence of local and supply chain abnormal precipitation on local agricultural GDP

Dependent Variable:	Agr. GDP growth			
Model:	(1)	(2)	(3)	(4)
Variables				
SPEI(1y) > 1 s.d.	-0.0013	-0.0639***	-0.0684***	-0.0632***
	(0.0103)	(0.0146)	(0.0161)	(0.0146)
SPEI(1y) < -1 s.d.	-0.0343***	-0.0485***	-0.0475***	-0.0462***
	(0.0081)	(0.0114)	(0.0117)	(0.0115)
Inpmts. remote SPEI(1y) < -1 s.d.		-0.0452***		-0.0382**
		(0.0168)		(0.0183)
Inpmts. remote SPEI(1y) > 1 s.d.		0.0020		0.0028
		(0.0348)		(0.0402)
Outpmts. remote SPEI(1y) < -1 s.d.			-0.0041	-0.0016
			(0.0027)	(0.0036)
Outpmts. remote SPEI(1y) > 1 s.d.			0.0039	-0.0062
			(0.0080)	(0.0048)
Local prec. lag	Yes	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes	Yes
Fixed-effects				
Municipality	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Fit statistics				
Observations	88,898	38,216	37,093	34,532
R^2	0.10702	0.17477	0.17924	0.18684
Within R^2	0.02613	0.03735	0.03806	0.03633

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

The first column of Table 9 highlights how sensible agriculture activity is to physical risks. A local dry spell leads, on average, to almost 3.5 percentage points less agricultural GDP growth. But incorporating supply chain effects identify more precisely even the effect of local shocks: when customer or supplier shocks are accounted for (columns 2-4), also wet spells are shown to be highly significant and material for agricultural economic growth.

The supply chain results for agricultural GDP also hint at a specific transmission mechanism for that sector. When only remote municipality pairs are considered, the importance of dry spells at customer municipalities becomes clear. If a municipality had all its observed income from remote customers, and they were subject to dry spells, local GDP growth would be circa 4 percentage points lower.

As shown in Table 10, climate shocks transmission through the supply chain may also affect manufacturing GDP growth. An interesting finding is that sensitivity to local droughts is significant, but smaller than the agricultural sector. As for supply chain transmissions, also here the inclusion of these effects explains a larger share of variation in sectoral GDP growth, with R^2 going from 7% to 11%. These regressions suggest that some shock transmission occurs when suppliers are undergoing a dry spell.

Table 10: Influence of local and supply chain abnormal precipitation on local manufacturing GDP

Dependent Variable:	Man. GDP growth			
Model:	(1)	(2)	(3)	(4)
Variables				
SPEI(1y) > 1 s.d.	-0.0124	-0.0078	-0.0111	-0.0068
	(0.0083)	(0.0117)	(0.0118)	(0.0120)
SPEI(1y) < -1 s.d.	-0.0247***	-0.0163**	-0.0139*	-0.0152*
	(0.0082)	(0.0081)	(0.0080)	(0.0081)
Inpmts. remote SPEI(1y) < -1 s.d.		-0.0363		-0.0413
		(0.0232)		(0.0272)
Inpmts. remote SPEI(1y) > 1 s.d.		0.0246		0.0075
		(0.0353)		(0.0447)
Outpmts. remote SPEI(1y) < -1 s.d.			-0.0033*	-0.0015
			(0.0019)	(0.0030)
Outpmts. remote SPEI(1y) > 1 s.d.			-0.0034	0.0003
			(0.0039)	(0.0163)
Local prec. lag	Yes	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes	Yes
Fixed-effects				
Municipality	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Fit statistics				
Observations	88,861	38,180	37,055	34,498
R^2	0.07050	0.11092	0.11312	0.12221
Within R^2	0.01108	0.01989	0.01957	0.02105

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table 11 shows the same analyses for the services sector. GDP growth also responds negatively to local physical risks, with each local shock depressing GDP growth between 0.7 and 0.9 p.p. This puts the sensitivity of services GDP to local shocks on a smaller scale as agriculture and manufacturing. And when only remote municipalities are considered, supply chain shocks do not seem to affect the services sector. The coefficients are almost all close to zero; the only coefficient with a comparable magnitude to other effects (also not statistically significant) is that of wet spells in distant suppliers, which hints at issues like logistics problems. Overall, the services sector does not appear to be affected by weather shocks transmitted through the supply chain network.

Table 11: Influence of local and supply chain abnormal precipitation on local services GDP

Dependent Variable:	Ser. GDP growth		
Model:	(1)	(2)	(3)
Variables			
SPEI(1y) > 1 s.d.	-0.0077**	-0.0109*	-0.0086
	(0.0032)	(0.0057)	(0.0053)
SPEI(1y) < -1 s.d.	-0.0086***	-0.0039	-0.0035
	(0.0030)	(0.0036)	(0.0036)
Inpmts. SPEI(1y) < -1 s.d.		0.0042	
		(0.0045)	
Inpmts. SPEI(1y) > 1 s.d.		0.0028	
		(0.0095)	
Outpmts. SPEI(1y) < -1 s.d.		0.0003	
		(0.0003)	
Outpmts. SPEI(1y) > 1 s.d.		0.0002	
		(0.0020)	
Inpmts. remote SPEI(1y) < -1 s.d.			0.0003
			(0.0107)
Inpmts. remote SPEI(1y) > 1 s.d.			0.0174
			(0.0124)
Outpmts. remote SPEI(1y) < -1 s.d.			-0.0010
			(0.0007)
Outpmts. remote SPEI(1y) > 1 s.d.			-0.0029
			(0.0031)
Local prec. lag	Yes	Yes	Yes
Local temp. lag	Yes	Yes	Yes
Local GDP lag	Yes	Yes	Yes
Fixed-effects			
Municipality	Yes	Yes	Yes
Year	Yes	Yes	Yes
Fit statistics			
Observations	88,932	41,719	34,548
R^2	0.10467	0.17599	0.20172
Within R^2	0.02310	0.03366	0.03223

Clustered (Region) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

6 Counterfactual exercises

Our setting allow an empirical counterfactual test of the relevance of explicitly modelling supply chain linkages between municipalities. We adapt the counterfactual exercises of Zappalà (2023) to study whether estimates of climate change on local GDP really encompasses in aggregate the wealth of local interactions that are reflected, for exampe, in trade interlinkages as claimed by Burke, Hsiang, and Miguel (2015), Burke and Tanutama (2019) and Kalkuhl and Wenz (2020).

The first step is to calculate SPEI counterfactuals. Given our network estimation starts in 2012, we use

precipitation and temperature data from 1961-2011 to calculate a linear trend through the coefficient β in $J_{imt} = \alpha_i + \lambda_m + \beta_i t + \varepsilon_{imt}$, where $J = \{P, T\}$ and m is the month of the year. Then we use the estimated slope for precipitation and temperature, $\widehat{\beta}^{(J)}$ to projecte a linear climatic path for each municipality between 2012 and 2019:

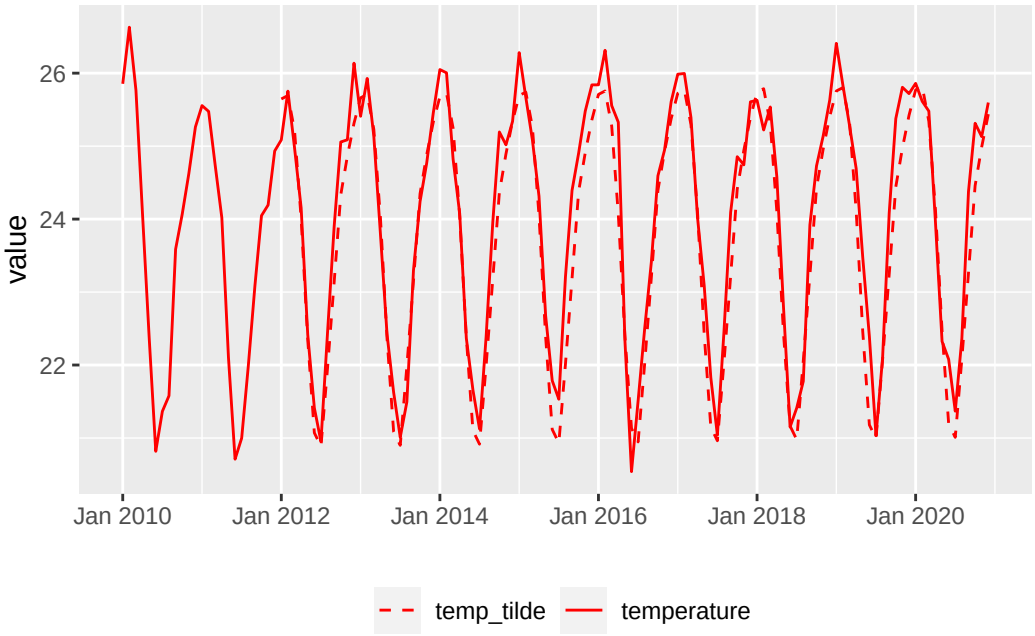
$$\begin{aligned} \tilde{P}_{t\in\{2012-2019\}} &= P_t + \widehat{\beta}_i^{(P)}(t - P_t) \\ \tilde{T}_{t\in\{2012-2019\}} &= T_t + \widehat{\beta}_i^{(T)}(t - T_t). \end{aligned} \tag{3}$$

Armed with these municipality-specific linear trends for precipitation and temperature, each conditional on past data, a counterfactual SPEI for each municipality is calculated, $\widetilde{\text{SPEI}}_{it}$. We then estimate climate change projections to calculate how "wrong" analyses that only consider local shocks would be on direct impact and on the volatility of aggregate Brazilian GDP. This analysis also allow us to approximate what share of the results are attributable to climate change in the last decades as opposed to long-standing physical risks.

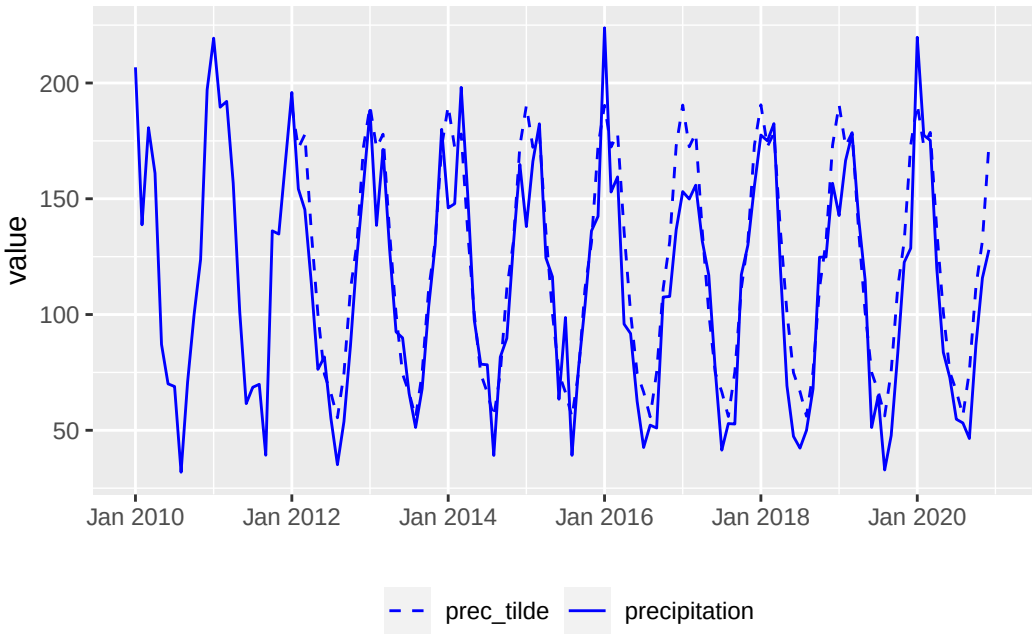
[Analyses in progress]

Figure 6: Average 12-months of actual and linear trend climate values, Brazil average

(a) Temperature



(b) Precipitation



7 Discussion

Before moving to the conclusion, a brief discussion on potential connection and on our findings related to adaptation is helpful.

Supply chains are not the only way that two economic locations can be connected. Multiple other channels can contribute to transmitting economic shocks. For example, financial integration through banks contributes to synchronising business cycles (eg, Kalemli-Ozcan, Papaioannou, and Perri (2013)), tourism flows are associated with economic integration (Khalid, Okafor, and Burzynska (2022)) and reliance on the same commodities for economic activity (Camacho and Perez-Quiros (2014)). In this paper, we do not explicitly model these other transmission channels. Instead, they are absorbed in year and municipality fixed effects,[9] with their year-municipality moving effects reflected in the residuals.

In addition, broader findings from the literature suggest that adaptation is limited at the aggregate level (Carleton and Hsiang (2016)), but some evidence suggests there is some level of adaptation at more disaggregated levels. Our results point to local precipitation being a significant control, including a meaningful interactor to supply chain shocks. However, a more targeted evaluation focused on analysing these local adaptation effects is warranted for stronger conclusions.

8 Conclusions

The analyses above take advantage of the geographic, climatic and economic variations found in Brazil to estimate the impact of physical risks on growth - both when these shocks occur locally and in other areas connected by trade. Our results present considerable evidence that both physical shocks impact local GDP growth and end up transmitting to other areas through supply chain connections. But the effects are heterogenous, with agricultural activity particularly sensitive to both local and remote shocks, followed by manufacturing. The services sector, in contrast, is sensitive to local climate conditions but appears to be more insulated on average from physical risks. Our findings also complement the literature as they point to the importance of *moderate* physical shocks. In contrast to a large of the physical risks literature, who traditionally study intense climate shocks, we find that moderate shocks are responsible for both local and supply chain effects.

Climate-related physical shocks are difficult to measure consistently as there are various classes of weather events (eg, droughts, heavy rains, floods, etc), and they are all uniquely complex in how natural occurring phenomena impacts cause economic losses. Some drivers of physical risks are associated with a larger amplitude of climate variations (ie, more extreme weather type of events) while others relate to longer-term, gradual change in temperature and precipitation levels. Hence, part of the literature relies on individual climate-related disasters to identify physical risks. But less consequential climate anomalies that are not catastrophic events, or even medium- to long-term anomalies such as heat waves or droughts that plays out in time also create physical risks. This paper focuses on this more complete picture of physical risks.

Our results also open up interesting new avenues for research: if supply chains transmit economic shocks related to physical shocks, to what extent are they also *shaped* by these occurrences? Can increased severity and frequency of climate anomalies, a perverse consequence from climate change, lead to reshaping of supply chains? And if local and supply chain physical shocks have such an effect on GDP, what percentage of GDP forecasting errors can they represent in aggregate? These are all questions we hope future research can answer.

[9] For example, year fixed effects control for all the different commodities prices.

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