The impact of weather shocks on exports

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Abstract

Previous research provides ample evidence that on their own international trade and weather shocks can be important drivers of economic growth, but we know relatively little about how these two factors might interact. This paper brings together recent approaches in international trade and climate econometrics to investigate the differential impact of weather shocks on exports relative to domestic sales, shedding light on the interaction of weather shocks with existing trade barriers. The results suggest that both manufacturing and agricultural exports are sensitive to weather shocks, but in notably different ways. Manufacturing exports are relatively resilient but see small decreases relative to domestic sales in response to increases in extreme heat days and total annual precipitation. Agricultural exports are relatively more sensitive to a more broad set of weather shocks, particularly increases annual mean temperature and temperature variance as well as increases in monthly rainfall relative to the climatic norm. I find some evidence that these effects are larger when existing trade barriers are already large, such as if trading partners do not share a border. Economists usually conceptualize the macroeconomic damages of climate change as productivity impacts, but these results provide some evidence that local weather shocks and potentially climate change can exacerbate existing barriers to international trade. Moreover, the results suggest that weather shocks propagate unequally through the international trade network, with importers that are more remote from international markets potentially more likely to be indirectly impacted by weather shocks in their exporting partners.

JEL codes: F13, F18, O13, Q17, Q54, Q56
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1 Introduction

A rapidly developing literature provides empirical evidence that extreme weather and climate change negatively impact economic outcomes (Dell et al. 2012; Burke et al. 2015; Kalkuhl and Wenz 2020). Such findings have led the IPCC to conclude with medium to high confidence that extreme weather and climate change have already impacted agricultural yields, labour productivity, and infrastructure around the world, and the risks of such impacts are likely to increase rapidly if global warming is not limited to 1.5°C (IPCC 2022). These risks highlight the importance of deepening our understanding of the potential economic impacts of further warming. Meanwhile, the literature on climate damages has paid relatively little attention to the role of international trade in the economic impacts of extreme weather and climate change; indeed, Dawson et al. (2020) undertake a quantitative textual analysis of recent IPCC assessments and find a lack of coverage of international trade in the reports. Nevertheless, international trade may interact with extreme weather and climate change in a range of potential ways; for example, access to international markets may help countries to adapt to climate change (Copeland et al. 2022), and changes in productivity across countries due to climate change may interact with international trade patterns to change the distribution of gains from trade across countries (Dingel et al. 2019). Another potential interaction between climate change and international trade is that weather shocks may impact the flow of goods to international markets.

This paper tests empirically whether temperature and precipitation shocks interact with barriers to international trade, shedding light on the extent to which weather shocks and climate change affect countries' connectedness to international markets. More specifically, I quantify the difference in the impact of

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weather shocks on the value of exports relative to sales in producers' domestic markets. In the context of the structural gravity framework that underpins the empirical model, these estimates can be understood as quantifying the impact of weather shocks on ad valorem tariff-equivalent trade barriers. While seminal contributions such as Dell et al. (2012) and Burke et al. (2015) estimate the impact of weather shocks and climate change on productivity - that is, the "size of the output pie" - this paper focuses on the impact of weather shocks on the "division of the pie" between exports and domestic market sales. Moreover, unlike previous empirical studies of international trade and weather shocks, which do not disentangle impacts on underlying productivity from a potential particular sensitivity of exports to weather shocks, I use an empirical model that allows me to test specifically for a difference in the effect of weather shocks on exports versus sales in the domestic market. The results reveal the impact of weather shocks on barriers to international trade.

Several potential mechanisms could explain why changes in temperature or precipitation might affect barriers to international trade. First of all, international trade patterns often exhibit a "home bias", suggesting that if weather shocks disrupt production, export quantities reduce more than domestic sales; Jones and Olken (2010) discuss this hypothesis, pointing out that greater volatility of exports compared to domestic sales in the face of a production shock is consistent with standard trade models. Furthermore, international supply chains may be more sensitive to to weather shocks than domestic supply chains because they are longer and also rely more heavily on vulnerable infrastructure such as ports. Becker et al. (2013) explain how the vulnerability of seaports to extreme weather and climate change could negatively impact international trade. Railways are also vulnerable to the impacts of weather shocks: Chinowsky et al. (2019) find that increased temperatures have caused costly delays in the US rail networks. These potential impacts of weather shocks on transport infrastructure suggest that weather shocks may increase barriers to international trade. Real-life examples from Malaysia and Argentina help to illustrate this hypothesis further. In 2021, flooding in Malaysia caused significant disruptions to the semi-conductor industry; this flooding not only led to disruptions at the production plants, but also made roads inaccessible and caused congestion and delays at Port Klang, an important port for international trade.[1] Also in 2021, dry conditions in Argentina caused water levels of the Parana River to drop so much as to become impassable for barges, reportedly causing exports to be diverted to much more costly road transport routes.[2]

Finally, another potential mechanism through which weather shocks may affect exports differently from domestic sales is through price effects: existing trade barriers may allow domestic prices to respond to a domestic production shock more than export prices. For example, suppose weather shocks lead to a decrease in domestic production. Existing barriers to trade may allow domestic producers to raise prices in their domestic market, while international competition prevents them from doing so in the export market. In this case, the value of an export sale decreases relative to the value of a domestic sale due to these price effects. An example from the Philippines illustrates these potential price effects. In 2019, unusually dry weather in the Philippines caused by the El Niño effect led to an oversupply of around 2 million kg of mangoes. According to local news reports, this excess supply was mainly absorbed by the domestic market, and local prices decreased by more than half. In this example, a weather shock led to a positive production shock and then a decrease in domestic prices relative to export prices.[3]

Although the hypotheses mentioned thus far suggest that exports may be more sensitive to weather shocks than domestic sales, a competing hypothesis suggests that the sign of this effect is actually ambiguous. That is, exports could be less vulnerable to weather shocks than domestic sales. A large literature on the propensity to export that tells us that firms that export are different from firms that do not (Atkin et al. 2017; Görg et al. 2012). Given that increased propensity to export is associated with mainly positive firm traits (e.g. higher productivity), this literature suggests that firms that export might be more resilient to weather shocks than firms that do not export. With this evidence in mind, we might expect that exports are less sensitive to weather shocks than domestic sales. The theoretical ambiguity of the effect of weather shocks on exports relative to domestic sales highlights the importance of investigating this question empiri-

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[1] See media coverage of the impact of the flooding in Malaysia here.

[2] See media coverage of this event here and here.

[3] See media coverage of the oversupply of Mangos here and here.

cally, and also justifies the use of two-sided tests throughout this paper to do so.

To estimate of the differential effect of weather shocks on exports relative to domestic sales, I combine gravity model estimation techniques from the trade literature with developments from the climate econometrics literature. Estimating the effect of weather shocks on trade is not straightforward given the potential biases inherent in empirical trade models. Models with international trade flows as the dependent variable are essentially cross-country comparisons and must inevitably deal with a myriad of potential confounding variables; how much two countries trade with each other is affected by complex array of factors, many of which are difficult to measure and observe. Accordingly, a huge body of work in international trade has focused on the best techniques to mitigate potential omitted variable bias. A key development has been the use of importer-time and exporter-time fixed effects to properly control for 'multilateral resistance', which has now become part of best practice standards for empirical trade studies (Baldwin and Taglioni 2006). However, following these best practices means that country-specific variables such as weather shocks are absorbed into fixed effects.

To overcome these challenges I follow the innovations in Heid et al. (2017) and Beverelli et al. (2018) to control for the multilateral resistance parameters with a full set of importer-time and exporter-time fixed effects while still estimating the effect of country-specific variables (such as weather shocks) on exports relative to domestic sales. This approach includes domestic as well as international trade flows in the model and interacts the variables of interest (temperature and precipitation in this case) with a dummy indicator for international sales. Heid et al. (2017) apply this methodology to measure the effects of most favoured nation (MFN) tariffs and "Time to Export" on international relative to domestic trade. Beverelli et al. (2018) build on the methodology of Heid et al. (2017) to estimate the effect of institutional quality on exports relative to domestic sales. They find that poor institutions hinder exports and their GE simulation suggests that this effect translates into notable impacts on GDP. Ultimately, the approach developed in these papers provides a more robust basis for causal inference compared to methods used in previous papers exploring the relationship between temperature and trade.

Previous literature has demonstrated that weather and climate have notable economic impacts on a macroeconomic level. A rapidly expanding area of work uses historical weather data to estimate empirically the impact of weather and climate and economic outcomes. A particularly strong focus in this literature has been the effect of weather and climate on GDP. Seminal contributions include Dell et al. (2012), Burke et al. (2015), Kalkuhl and Wenz (2020), and Newell et al. (2021). This body of work contributes important empirical evidence to complement model-based estimates of the economic damages of climate change. Two key methodological developments in the climate econometrics literature have been the use of panel data techniques to deal with biases in cross-sectional analyses and functional forms that allow for non-linear effects of weather on economic outcomes. I follow these developments in the climate change economics literature, using a panel data setting and allowing for nonlinear effects of weather shocks; the main specification is a quadratic functional form for the effects of temperature and precipitation variables on trade.

Another important and ongoing debate in the climate econometrics literature relates to the measurement of weather shocks. While early contributions use straightforward measures such as annual mean temperature and total annual precipitation, recent contributions show that the economy is sensitive to other types of weather shocks that are not easily captured by these straightforward measures. For example, Linsenmeier (2024) shows that inter-annual temperature variability is a key driver of seasonal cycles in GDP, and Kotz et al. (2021) shows that increased day-to-day variation in temperatures lead to decreased productivity. Meanwhile, Kotz et al. (2022) study the economic impacts of precipitation shocks by including measures of precipitation variation and extreme precipitation as well as total annual precipitation to thoroughly test for and identify the types of precipitation shocks that are particularly relevant for economic activity. In the spirit of this ongoing empirical debate on measuring weather shocks, this paper follows the approach of Kotz et al. (2022) to include not just annual mean temperature and total annual precipitation in the model, but also measures of variation and extremes of temperature and precipitation. This approach allows me to hone in on the type of weather shock that is particularly relevant to exports and trade barriers.

Within the broad climate econometrics literature, this paper contributes to the relatively small body of work that studies the impacts of weather shocks on international trade. This literature provides some evidence that increased temperatures are associated with a reduction in exports. For example, an early empirical contribution by Jones and Olken (2010) finds that increased temperatures are associated with reduced export growth in poor countries. The magnitude of their estimate is larger than the effect of temperature on GDP estimated in Dell et al. (2012), which they briefly suggest may indicate that exports are more sensitive to temperature than GDP but do not investigate any further.[4] More recently, several papers have employed gravity-like models for ex-post studies of the impact of weather shocks on international trade (Osberghaus 2019; Dallmann 2019; Osberghaus and Schenker 2022). The evidence from these studies suggests that increased temperatures reduces trade, with the agriculture sector particularly affected, while the effect of precipitation on trade is ambiguous. However, these papers often identify the effect of weather shocks on trade by reducing the set of fixed effects usually used in gravity models, and they do not separately estimate the effect of weather shocks on productivity from the effect on the flow of trade. As a result, this literature does not address the question of whether exports are particularly sensitive to weather shocks, or if these papers simply capture the impact of weather shocks on productivity through the lens of trade data. This paper specifically tests for and quantifies the relative sensitivity of exports to weather shocks by directly comparing domestic sales and exports within the same empirical model.

Another related body of empirical literature studies how international linkages can cause the local productivity impacts of local weather shocks to propagate and have cross-border impacts. For example Feng and Li (2021) show that weather shocks in trading partner countries are associated with a decrease in stock market valuation. Dingel et al. (2019) show that in the event of a shock such as an El Niño year, an increase in the spatial correlation in absolute advantage agricultural cereal productivity leads to an increase the inequality of welfare gains from trade. Osberghaus and Schenker (2022) use a structural gravity framework to show how increased extreme heat days have not only direct impacts on a producing country, but also indirect effects on their trading partners. Zappalà (2023) uses sector-level input-output data to make a similar point on the propagation of weather shocks through supply chains. The results of the current paper contribute to this growing body of evidence that the impacts of local weather shocks extend beyond international borders. The key contribution of this paper to the literature on the cross-border effects of local weather shocks is that I allow trade barriers to change in response to weather shocks (rather than assuming that they remain constant) while also robustly controlling for other bilateral and country-specific factors that drive trade barriers. This approach allows me to study how local weather shocks propagate *unequally* through the global trade network due to the interaction of weather shocks with existing trade barriers.

In short, we know from previous work that weather shocks such as increased temperature variation and extreme heat are associated with decreased productivity, and that this effect translates into a decrease in exports, which then reverberate through supply chains and negatively impacts trade partners. This paper builds on this work by specifically testing for and quantifying the particularly sensitivity of exports to weather shocks compared to domestic sales. The results provide evidence that exports from both the manufacturing and agriculture sectors are more sensitive to weather shocks than domestic sales, suggesting that weather shocks are associated with an increase in trade barriers. Moreover, I document notable differences between these sectors in the types of weather shocks to which they are sensitive; agricultural exports are sensitive to increases in annual mean temperature, temperature variance, and increases rainfall from the climatic norm, while manufacturing sector exports are relatively resilient but show sensitivity to increases in extreme heat days and total annual precipitation. Finally, I assess the heterogeneity in these affects with respect to bilateral characteristics and show that these increases in trade barriers in response to a weather shock are larger when existing trade barriers - such as geographical distance or the lack of a shared border - are already large. These results highlight the role of trade barriers in the propagation of weather shocks through the global economic system, implying that the impacts of weather shocks propagate unequally such that buyers that face the highest trade barriers before the weather shock are most exposed to the indirect supply-chain impacts of the shock.

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[4] The aim of their paper is not to investigate specifically the impact of temperature on trade, but to confirm (through the lens of data on US imports) that their previous finding that temperature impacts economic productivity in poor countries is robust and not due to the potentially poor quality of GDP data.

The remainder of the paper is organized as follows. The next section outlines the methodology used in this study, providing a brief theoretical background before describing the empirical model. Section 3 describes the data, including how I construct the temperature and precipitation variables, and then Section 4 presents and discusses the empirical results. Finally, Section 5 concludes.

2 Methodology

The following section outlines the methodology used to estimate a differential effect of weather shocks on exports relative to domestic sales. First I outline a standard theoretical basis for the empirical trade model and explain the challenges of estimating the effects of unilateral variables such as weather shocks on bilateral trade. Then I present the estimating equation, and finally I explain how to interpret the coefficient estimates and how they relate to the marginal effects of interest.

2.1 Theoretical background

The structural gravity model, often dubbed the 'workhorse' of international trade analyses, can be derived from several different micro-foundations, all of which lead to the following standard expression for bilateral trade (Head and Mayer 2014):

$$X_{ijk,t} = \frac{Y_{ik,t}}{\Omega_{ik,t}} \frac{E_{jk,t}}{\Phi_{jk,t}} \phi_{ijk,t} \tag{1}$$

In this expression, $X_{ijk,t}$ is the value of bilateral trade in industry k sold by exporter i to importer j in period t. $Y_{ik,t}$ and $E_{jk,t}$ are the value of the exporter i's total production and the value of importer j's total expenditure, respectively, in industry k and period t. $\phi_{ijk,t}$ is the bilateral accessibility of exporter i to importer j; this term includes the cost to transport goods from i to j as well as less-quantifiable trade barriers such as cultural and institutional differences between i and j.

$\Omega_{ik,t}$ and $\Phi_{jk,t}$ are the importer and exporter multilateral resistance parameters in industry k and year t; they describe how well-integrated buyers and sellers in a given country are into the global trade network in a given year. $\Omega_{ik,t}$ summarizes how well sellers in country i can access buyers around the world, and $\Phi_{jk,t}$ summarizes how well consumers in country j can access products from around the world (Head and Mayer 2014). These parameters are essential components of the model, and not controlling for them properly has been dubbed the "gold medal mistake" of estimating structural gravity models (Baldwin and Taglioni 2006). Standard practice in a panel data setting is to control for these terms using importer-industry-year and exporter-industry-year fixed effects, and Head and Mayer (2014)'s Monte Carlo simulations demonstrate the superiority of this approach over other ways to control for the multilateral resistance parameters. However, these importer-industry-year and exporter-industry-year fixed effects absorb all country-specific characteristics that are invariant across trade partners, preventing the researcher from estimating the effect of country-specific variables such as GDP, national policies, institutions, and weather. This challenge is the main difficulty in studying the effect of weather shocks on international trade; we seem to have a trade-off between including country-specific variables such as temperature and precipitation in the above model and using best practices for robust gravity model estimation.

Head and Mayer (2014) review possible approaches to estimating country-specific effects in gravity models; at the time of their writing, they find that the literature lacks a single satisfying approach. One common way that papers deal with this challenge is forgoing the importer-time and exporter-time fixed effects. For example, Dallmann (2019) estimates the effect of temperature and precipitation on international bilateral trade by not including importer and exporter fixed effects and instead relying on observable country-specific variables (such as GDP) and country-pair fixed effects to deal with potential endogeneity. The benefit of this approach is that the researcher is able to identify the full effect of weather variables on bilateral trade flows. The key disadvantage of this approach is that it cannot control for unobservable potential confounding variables which vary at the importer-time or exporter-time level and affect bilateral trade and are correlated with the weather variables. For example, an exporter's overall connections to the global trading network

($\Omega_{i,t}$ in Equation 1, known as outward multilateral resistance in the gravity literature), is an important determinant of bilateral trade. If weather shocks affect one bilateral relationship, this effect will spill over into the exporter's other bilateral relationships via their multilateral resistance. Without exporter-year fixed effects to control for outward multilateral resistance, we cannot isolate the direct effect of weather shocks on trade from the effect of outward multilateral resistance. Finally, weather shocks are certainly correlated with underlying productivity in a given year, so without exporter-year fixed effects we cannot identify whether exports are particularly sensitive to weather shocks relative to overall sales.

This paper takes a recently-developed approach to overcoming the challenges associated with estimating the effect of weather on trade. I follow the method developed in Heid et al. (2017) and Beverelli et al. (2018) to control for multilateral resistances with importer-industry-year and exporter-industry-year fixed effects and estimate the effect of temperature shocks on international *relative* to domestic trade. The cornerstone of this approach is to include domestic trade flows (i.e. $i = j$) in the model. Heid et al. (2017) show that this design enables the researcher estimate the interaction between a dummy variable indicating international (versus domestic) trade and the country-specific variable of interest (e.g. temperature). For a proof that the parameter of interest is identifiable (and not collinear with any other model parameters) see the appendix of Heid et al. (2017). Importantly, this method cannot provide an estimate of the direct effects of temperature and precipitation on all sales (domestic and international), because they are absorbed by the fixed effects. However, this model does provide an estimate of the differential effect of weather shocks on exports compared to domestic sales. This estimate provides insight into whether exports may be more or less sensitive to weather shocks compared to domestic sales, an issue that hasn't been fully addressed by previous literature. As discussed in the Introduction of this paper, weather shocks may affect not simply how much is produced and sold overall, but also where these sales are made (domestic versus foreign markets).

2.2 Empirical model

To answer this question of whether temperature and precipitation differentially affect exports relative to domestic sales, I use an empirical counterpart to the theoretical gravity model in Equation (1). A common approach to derive an estimating equation from a multiplicative model such as Equation (1) is to log-linearize the expression and use the OLS estimator. However, Silva and Tenreyro (2006) show that in the presence of heteroskedasticity (which is ubiquitous in trade data), the OLS estimator is biased when applied to a log-linear version of a multiplicative model. As a result, standard practice in the applied trade literature is to use the PPML estimator to estimate Equation (1). The PPML estimator also has the advantage of being able to take account of zero trade flows, which are another prominent feature of trade data (Yotov et al. 2016). My empirical model is:

$$\begin{aligned} X_{ijk,t} =& exp[\boldsymbol{\beta}_1(INTL_{ij} \times \boldsymbol{T}_{i,t}) + \boldsymbol{\beta}_2(INTL_{ij} \times \boldsymbol{P}_{i,t}) + \pi_{ik,t} + \chi_{jk,t} + \mu_{ijk} + \alpha RTA_{ij,t} \\ &+ \eta INTL_{ij} \times YEAR_t] \times \varepsilon_{ijk,t} \end{aligned} \tag{2}$$

$X_{ijk,t}$ is the value of industry k bilateral trade flows from exporter i to importer j in year t, and importantly this variable includes within-country sales - i.e. cases when $i = j$. $\boldsymbol{T}_{i,t}$ and $\boldsymbol{P}_{i,t}$ are vectors of temperature and precipitation variables that describe weather conditions in the exporting country i in year t. These vectors include a measure of the central tendencies of temperature and precipitation in a given year (annual mean temperature and total annual precipitation), measures of the variation temperature and precipitation (variance of daily temperatures and monthly rainfall deviations), and measures of the upper tail of temperature and precipitation (number of extreme heat days and extreme daily rainfall). Moreover, I allow for non-linear effects by including the square of the variables. See Section 3 below for an in-depth description of these variables. The vectors of weather variables are interacted with with a dummy variable indicating export (rather than domestic) sales, $INTL_{ij}$, allowing me to identify any differential effect of weather on exports relative to domestic sales.

A statistically significant estimate for the coefficients in the vectors $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ suggests that weather shocks affect not just productivity (as suggested by other studies in the climate econometrics literature) but also the share of this production that flows to domestic versus foreign markets. In a hypothetical "frictionless" world without any transportation costs or other trade barriers, we would expect that even if weather shocks affect underlying production, it should have on bearing on whether that production is sold domestically or exported, since trade is costless no matter how close or far the buyer is from the seller. In this sense, this papers tests if weather shocks interact with existing trade barriers (in particular, the presence of an international border) to affect the flow of trade.

The model includes exporter-importer-industry fixed effects, μ_{ijk}, which control for industry-specific time-invariant factors that affect the accessibility of import market j to exporter i. These controls absorb a myriad of factors that affect trade costs such as distance, geography, and cultural ties. Alongside these time-invariant drivers of trade costs, we would expect that changes in trade agreements over the sample period also affect trade costs, and I control for these effects with the $RTA_{ij,t}$ dummy variable, which indicates whether exporter i and importer j are part of a common regional trade agreement in year t. The $INTL_{ij} \times YEAR_t$ dummy variables control for the average level globalization in a given year across all countries, an innovation which Bergstrand et al. (2015) find plays an important role in reducing bias in empirical gravity models. As discussed in the previous section, I also include exporter-industry-year ($\pi_{ik,t}$) and importer-industry-year ($\chi_{jk,t}$) fixed effects, which absorb anything that varies at the exporter-industry-year and importer-industry-year level, such as industry-specific productivity, multilateral resistances, and the impact of weather shocks on productivity. Nevertheless, the relative effects of weather on exports compared to domestic sales remains identifiable in the presence of this strict set of fixed effects.

These choices for modelling the relationship between weather and trade flows follow developments in the climate econometrics literature. Following Dell et al. (2012), the use of panel data techniques to deal with the biases in cross-sectional analyses has become widespread in studies estimating the effects of weather and climate on economic outcomes. A panel specification with country fixed effects means that the model identifies the effects of weather shocks (deviations from countries' average weather) on economic outcomes; Kolstad and Moore (2020) explain that in a linear model these effects are short-run responses, and if adaptation opportunities are strong then extrapolating climate change effects from the effects of weather shocks is problematic. One way to deal with this issue to some extent is to introduce non-linearities into the effect of weather shocks on economic outcomes. Burke et al. (2015) make a seminal contribution demonstrating the importance of allowing for non-linearities in these relationships. Kolstad and Moore (2020) explain that allowing for non-linear effects means that the estimate is a mix of short- and long-run responses. The main specifications in this paper follow Burke et al. (2015) in using a quadratic functional form for the relationship between bilateral trade and the weather variables in $\boldsymbol{T}_{i,t}$ and $\boldsymbol{P}_{i,t}$. Compared to previous studies investigating the effect of weather on trade (which mainly use linear functional forms), this approach should help to address the challenge of connecting estimates of weather effects to climate change effects to some extent. Importantly, like many econometric studies of the economic impacts of weather and climate change, my approach does not take into account potential changes in the climate system in response to economic activity, and therefore I assume that temperature and precipitation are weakly exogenous to the flow of trade (Pretis 2021).[5]

2.3 Interpreting model estimates

Given that the empirical specification is not a straightforward linear OLS model, a few important points on interpreting the model estimates are worth emphasizing. First, since the empirical specification uses the PPML estimator, the marginal effects are semi-elasticities, and second, the underlying effect of weather on productivity is absorbed into the exporter-industry-year fixed effects, so the empirical model only identifies the effect of weather on exports *relative* to domestic sales. The effects presented in the results below are therefore the difference in the semi-elasticity of exports with respect to a weather shock versus the semi-elasticity of domestic sales. Next, since the weather effects are quadratic the effects vary over the distributions of the weather variables and the coefficients must be interpreted with this non-linearity in mind. For small (1 unit) weather shocks, I use the calculus method to compute effects, and for shocks larger than 1 unit I use the finite difference method (i.e. the difference in predicted trade for exports versus domestic sales). I also

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[5] Results from the Im, Pesaran, Shin test suggest that my temperature and precipitation variables are stationary (see Table 3 in the appendix).

show ad valorem tariff-equivalent effects to aid interpretation and comparison of the economic magnitude of the effects (see the Appendix for an explanation of how I calculate tariff-equivalent effects).

3 Data

The empirical model outlined above requires a cross-country panel dataset of bilateral trade flows, including domestic trade, plus data on regional trade agreements and data on weather in the exporting country. I outline the sources and construction of these variables below. The final dataset spans manufacturing and agriculture trade in 165 countries over 1991-2019; it is an unbalanced panel due to missing domestic trade data for some years for some countries. Table 1 lists summary statistics for the model variables.

Table 1: Summary statistics

	Mean	Median	Std deviation
International trade (Million USD)			
Manufacturing	5.31	0.00	139.75
Agriculture	2.00	0.00	42.99
Domestic trade (Million USD)			
Manufacturing	3263.62	213.76	17708.80
Agriculture	963.68	52.37	6506.76
Weather			
Average annual temperature (°C)	18.67	20.38	7.38
Extreme heat days	62.66	40.81	63.35
Total annual precipitation(mm)	1181.59	1008.87	829.31
Monthly rainfall deviations	-0.02	-0.03	0.42
Extreme daily rainfall (mm)	242.97	122.03	438.27

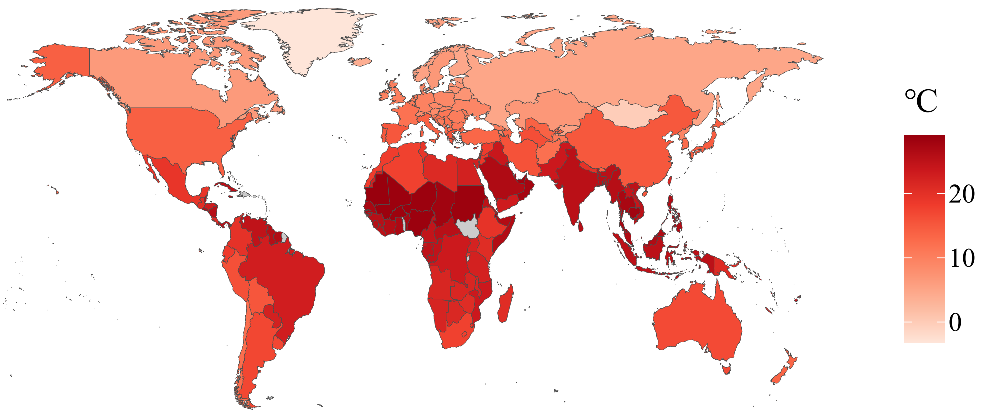
ITPD-E Database. Data on bilateral international trade flows as well as domestic trade is from Release 2 of the International Trade and Production Database for Estimation (Borchert et al. 2021; Borchert et al. 2022). This database provides industry-level observations for 28 agricultural industries and 118 manufacturing industries. These industries are internally consistent within the ITPD-E sample period and enable consistent comparisons across time despite changes during this period in standard industrial classification taxonomies such as ISIC. As is common practice in the international trade literature, missing bilateral trade is assumed to represent zero trade and therefore the matrix of international bilateral trade flows is complete. Domestic trade is constructed as the difference between output and total exports: $X_{ii} = Y_i - \sum_{i \neq j} X_{ij}$. Crucially, since international trade flows are observed in gross values, the authors of this database use gross values of production (not value-added) to construct domestic trade. Limitations in the availability of data on gross value of production is the most significant factor defining the spatial and temporal coverage of the sample.

CEPII Gravity. For all estimations, I use the Regional Trade Agreement (RTA) dummy from the CEPII Gravity database (Conte et al. 2022). This variable indicates whether or not two countries have a regional trade agreement in a given year. For domestic trade observations, I set this this dummy equal to zero. For the analysis of the heterogeneity of the results I use two additional variables from this database: the (population-weighted) geographical distance between importer and exporter pairs, and a dummy variable indicating whether two countries share a border.

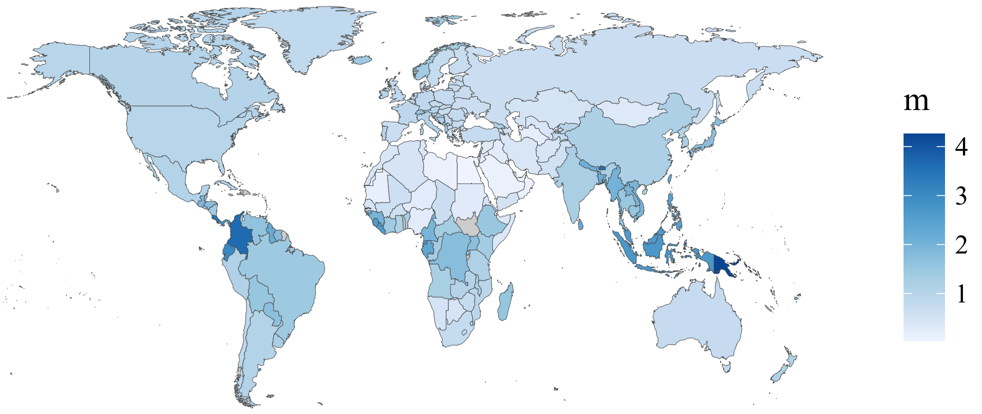
ERA5 Global Reanalysis. Data on temperature and precipitation are from ECMWF's ERA5 database (Hersbach et al. 2020). Using the hourly gridded data for 2 metre surface temperature and for precipitation rate I compute the average annual temperature and total annual precipitation for each grid cell. I then spatially aggregate to the country-level by taking the population-weighted average across all grid cells in a given country, using the Gridded Population of the World v4 dataset for the year 2000 (Center for International

Figure 1: Average weather across sample countries, 1991-2019

A. Average annual mean temperature



B. Average total annual precipitation



Earth Science Information Network - CIESIN - Columbia University 2018). Figure 1 illustrates the average of the annual mean temperature and total annual precipitation variables across sample countries and years. I test for unit roots in both the temperature and precipitation variables but do not find any evidence that either is non-stationary (see Table 3 in the Appendix for details of these tests).

In addition to average annual temperature and total annual precipitation, I also construct measures to reflect the degree of variation in temperature and precipitation in each year of my sample period. For temperature, I simply compute the variance in daily temperatures across a given year. For precipitation, I follow the approach in Kotz et al. (2022) to construct standardized monthly rainfall deviations, which represent the annual sum of deviations in monthly rainfall from the climate norm (see the appendix of Kotz et al. (2022) for more details). This measure is standardized such that it ranges between -1 and 1, with 0 indicating that rainfall corresponds exactly to the climate norm. To determine the climate norm I take the average monthly rainfall across 1981-2010.[6]

Finally, I also construct measures of extreme temperature and precipitation: extreme heat days and extreme daily rainfall. First, for each grid cell, I compute the climate norm for temperature and precipitation

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[6] I choose this period following the World Meteorlogical Association's standard for defining climate norms.

as the distribution of daily temperature and precipitation (once again using 1981-2011 to define the climate norm), and then I compute the 95th percentile of this distribution. To compute extreme heat days at the grid cell level, I count the number of days within a given year that temperature is above the 95th percentile of the climate norm for that grid cell. To compute extreme daily precipitation, I sum up precipitation on days that are above this threshold. As above, I spatially aggregate these measures of extreme weather to the country-level using a population-weighted average across grid cells in each country, as above.

Exporter characteristics. I explore heterogeneity in the effects of weather on trade according to a couple exporter characteristics: income and institutions. The Low $\text{income}_{i,t}$ dummy variable indicates whether country i was classified by the World Bank as 'Low income' or 'Lower middle income' in a given year (The World Bank 2022). The Weak $\text{institutions}_{i,t}$ dummy variable indicates whether country i is below the median observed value in year t for an institutional quality index. The institutional quality index is constructed as an unweighted average of the six variables in the World Governance Indicators dataset: control of corruption, government effectiveness, political stability and absence of violence, rule of law, regulatory quality, and voice and accountability (The World Bank 2020).

4 Empirical results

4.1 Main results

Figure 2 illustrates the estimated effects of weather shocks on exports relative to domestic sales for the empirical gravity model described in Section 2.2. Table 2 shows the underlying coefficient estimates. The plots show the estimated difference in the semi-elasticity for exports relative to domestic sales across the distribution of the weather variable. For all except extreme heat days and monthly rainfall deviations I show the marginal effect of a 1 unit increase (calculated using the calculus method); for the remaining two weather variables I show the full predicted effect relative to zero (calculated using the finite difference method. Given notable heterogeneity in the results between the manufacturing and agriculture sectors, I present results separately for these two sectors throughout this discussion. The histograms below the effect curves depict the sample distribution of the weather variable in the plot above.

Panel A illustrates the difference in the marginal effect on exports versus domestic sales of annual mean temperature across the sample distribution of this variable. The impacts of temperature shocks on the flow of trade are quite heterogeneous across these two sectors, with manufacturing exports being relatively resilient to temperature increases, while agricultural exports show an imprecise but on average negative response to temperature shocks relative to domestic sales. At the sample average of 18.7°C, the semi-elasticity of agricultural exports to a 1°C increase in annual mean temperature is 8.7 percentage points (s.e. 0.044) lower than the semi-elasticity of domestic sales. This relative sensitivity of exports may be slightly stronger in hotter places, but this non-linearity is not precisely estimated. Meanwhile, manufacturing exports are not more sensitive than domestic sales to an increase in annual mean temperature and in relatively cool countries exports increase slightly relative to domestic sales in response to increases in average annual temperatures.

The impact of annual variance in daily temperatures, as illustrated in panel B of Figure 2, is similarly heterogeneous across the two sectors: manufacturing exports have no statistically significant response to increases in temperature variance, while agricultural exports decrease in response to an increase in temperature variance. At the sample mean of $36.1°\text{C}^2$, a one unit increase in temperature variation leads to an 11.7 percentage point (s.e. 0.125) decrease in agricultural exports relative to domestic sales. This effect is stronger for countries that typically see relatively little annual variation in daily temperatures, which may suggest that countries adapt to a given level of annual temperature variance.

Next, the results depicted in Panel C suggest that after controlling for annual mean temperature and temperature variance, agricultural exports are not negatively impacted by extreme heat. At 60 or greater extreme heats days per year, the marginal effect of an additional extreme heat day is very slightly higher (more positive) for exports relative to domestic sale; however, the full predicted effect relative to zero extreme heat days is not significantly different for exports compared to domestic sales. Taken together with the results in

Table 2: Estimated effects of weather on exports relative to domestic sales

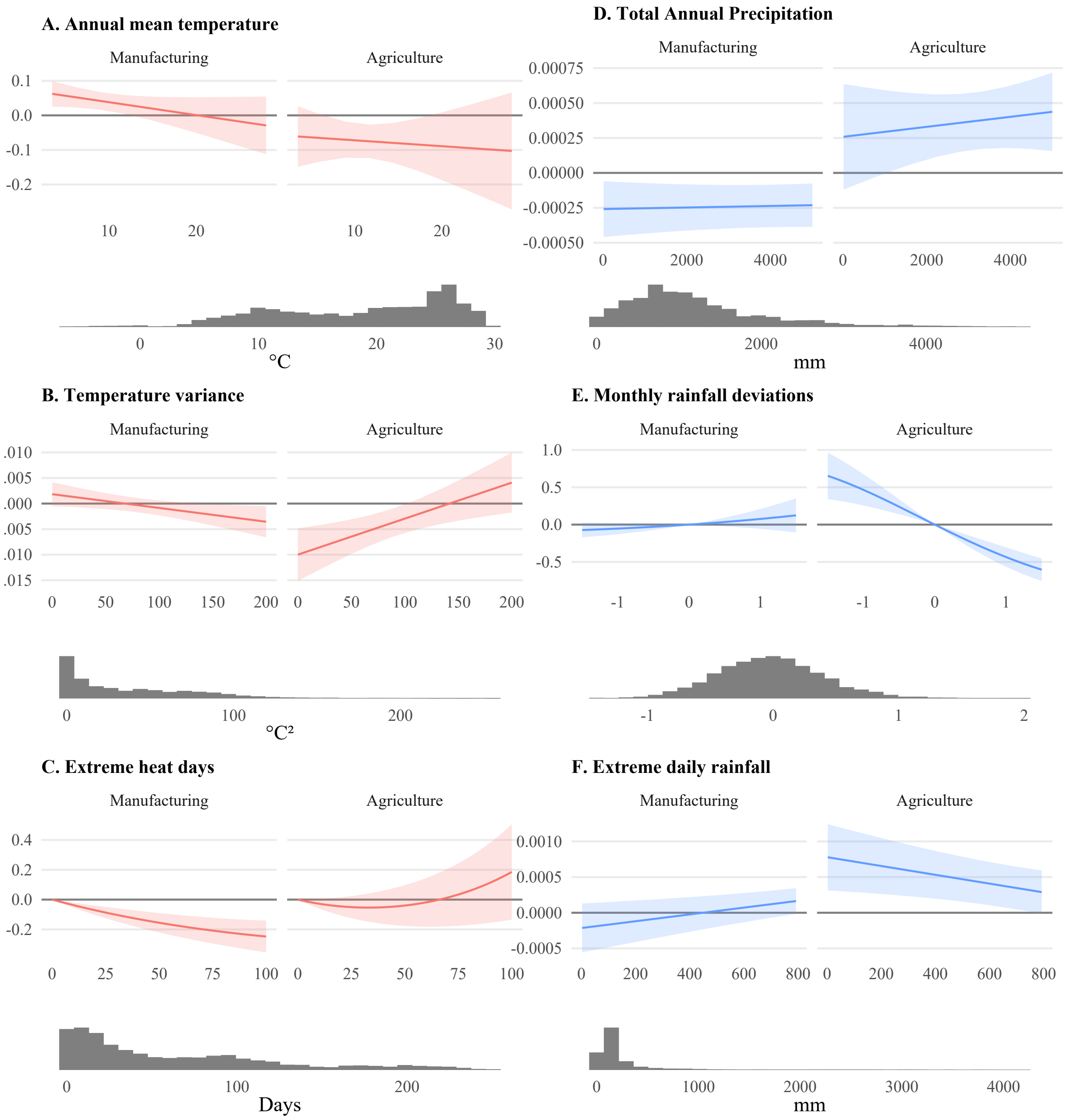
	Manufacturing	Agriculture
Temperature		
Annual temperature × INTL	0.075**	-0.055
	(0.025)	(0.060)
Annual temperature^2× INTL	-0.002+	-0.001
	(0.001)	(0.002)
Temperature variance × INTL	0.002	-0.010***
	(0.001)	(0.003)
Temperature variance^2× INTL	0.000*	0.000**
	(0.000)	(0.000)
Extreme heat days × INTL	-0.004***	-0.003+
	(0.001)	(0.002)
Extreme heat days^2× INTL	0.000+	0.000***
	(0.000)	(0.000)
Precipitation		
Annual precipitation × INTL	0.000*	0.000
	(0.000)	(0.000)
Annual precipitation^2× INTL	0.000	0.000
	(0.000)	(0.000)
Precipitation deviations × INTL	0.046	-0.288***
	(0.031)	(0.057)
Precipitation deviations^2× INTL	0.009	-0.094***
	(0.013)	(0.026)
Extreme daily rainfall × INTL	0.000	0.001**
	(0.000)	(0.000)
Extreme daily rainfall^2× INTL	0.000**	0.000*
	(0.000)	(0.000)
RTA	0.057*	0.097***
	(0.023)	(0.026)
Observations	53352805	5748969
INTL-Year FE	X	X
Exporter-Importer-Industry FE	X	X
Importer-Year-Industry FE	X	X
Exporter-Year-Industry FE	X	X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Standard errors (in parentheses) clustered by importer-exporter. The dependent variable is the value of bilateral trade for industries in the sector in the column heading. The exporter-industry-year fixed effects absorb the underlying effect of weather on output, so the coefficient estimates on the weather variables represent the *difference* in the effect on the flow of goods to export markets relative to the domestic market.

Panels A and B, these results suggest that agricultural exports are broadly sensitive to temperature shocks but not specifically vulnerable to extreme heat days; after controlling for annual mean temperature and variance in daily temperatures, extreme heat days do not provide additional information on the sensitivity of exports. Meanwhile, while manufacturing exports are relatively resilient to increases in annual mean temperature and temperature variance, Panel C suggests that they are specifically vulnerable to extreme heat days. At the sample mean of 36 extreme heat days per year, the semi-elasticity of manufacturing exports with respect to an additional day is 2.6 percentage points (s.e. 0.0007) lower than the semi-elasticity of domestic sales. This particular vulnerability of manufacturing exports to extreme heat could suggest that labour productivity or transport infrastructure vulnerability to extreme heat are potential mechanisms for

Figure 2: Difference in effect of weather shocks on exports relative to domestic sales



Notes: All plots depict the difference in the marginal effect of a 1 unit changefor exports relative to domestic sales, except for plots C (Extreme Heat Days) and E (Monthly Rainfall Deviations), which show the difference in the full predicted effect relative 0 extreme heat days or 0 monthly rainfall deviations. Error bands represent 95% confidence intervals. The histograms show the distribution of the weather variable across all exporter-years in the estimation sample.

the sensitivity of exports to temperature shocks. Overall the results for the temperature variables show that exports from both the agriculture and manufacturing sectors are sensitive to temperature shocks, but in different ways. Exports from the agricultural sector seem to be broadly sensitive to changes in temperature patterns throughout the year, while manufacturing exports are relatively resilient and mainly sensitive to extreme heat.

Next, panels D, E, and F depict the effects of total annual precipitation, monthly rainfall deviations, and extreme daily rainfall on exports relative to domestic sales. Once again the effects are quite heterogeneous across the two sectors. First, manufacturing exports decrease relative to domestic sales in response to an increase in total annual precipitation, but after controlling for this effect monthly rainfall deviations and extreme daily rainfall do not have an additional statistically significant impact. At the sample mean of 1182 mm of annual precipitation, the semi-elasticity of manufacturing exports to a 1 mm increase in total annual precipitation is 0.03 percentage points (s.e. 0.00009) lower than the semi-elasticity of domestic sales. The magnitude of this effect is fairly steady across different levels of annual precipitation, which could suggest that adaptation opportunities are limited.

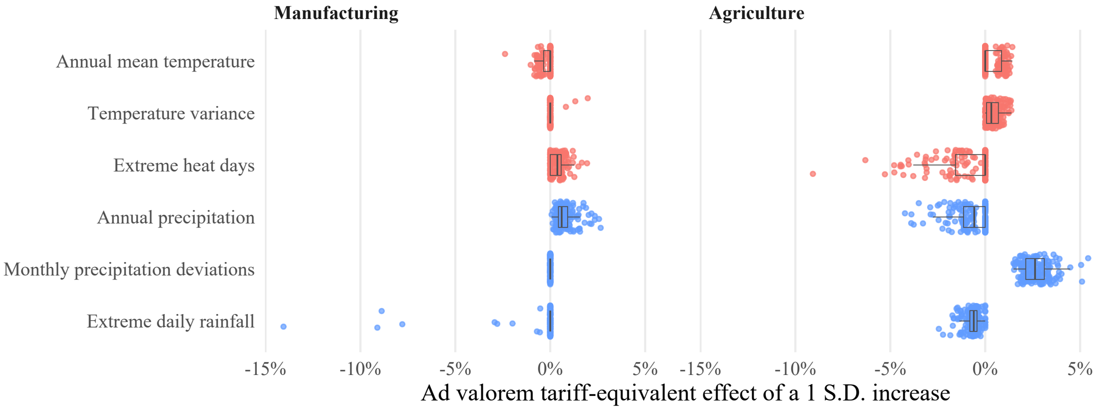
The response of agricultural exports to precipitation shocks shows interesting heterogeneity across the types of precipitation shocks. Agricultural exports decrease relative to domestic sales in response to increases in monthly precipitation relative to the climate norm, but they *increase* relative to domestic sales in response to increases in total annual precipitation and extreme daily rainfall. Given the findings from previous literature that agricultural production may increase in response to increases in precipitation (Kotz et al. 2022; Damania et al. 2020), these results are consistent with the story that producers look to international markets to absorb the increased agricultural production that may result from increased precipitation. Meanwhile, the sensitivity of agricultural exports to monthly rainfall deviations is consistent with Kotz et al. (2022)'s finding that this sector is particularly sensitive to this type of shock. These results broaden this finding, suggesting that exports are relatively more sensitive than domestic sales to an increase in monthly rainfall: at a one standard deviation increase in monthly rainfall deviations the effect on exports is 43.5 percentage points (s.e. 0.066) lower than the effect on domestic sales.

Overall, these results confirm previous findings that exports can be sensitive to weather shocks. Importantly, the results extend previous findings by confirming that this sensitivity does not simply reflect the productivity impacts of weather shocks, but that weather shocks lead to a shift in the balance of trade between exports and domestic market sales. For the agriculture sector, increases in annual mean temperature and temperature variance shift the balance of trade away from export markets and towards the domestic market, while the same occurs for manufacturing exports in response to increases in extreme heat days and total annual precipitation. Effectively, the trade barrier of an international border becomes larger in response to these weather shocks. An important aspect of these results is that the nature of the sensitivity of exports to weather shocks varies significantly across sectors and types of weather shocks. Agricultural exports are more sensitive in general than manufacturing exports, and the strongest effects seem to be the impact of monthly rainfall deviations on agricultural exports and the impact of extreme heat on manufacturing exports. Nevertheless, the economic significance of these results are difficult to compare across the different weather shocks due to the different units of measurement and the differences in the shape of the cross-country sample distribution of the weather variables. The next section deepens the assessment of the economic significance of these results by calculating tariff-equivalent effects.

4.2 Tariff-equivalent effects

Figure 3 calculates for each sample country the predicted change in trade (calculated using the finite difference method) of a 1 standard deviation increase from the mean of the weather variable. The mean and standard deviation are calculated separately for each country. The predicted change in exports is then converted into an ad valorem tariff-equivalent effect by assuming a value of -5 for the trade elasticity of substitution, which follows Head and Mayer (2014)'s preferred value for this parameter. While this conversion of predicted effect into a tariff-equivalent effect has the disadvantage of relying on the calibration of this parameter, the advantage of the approach is that allows for an intuitive interpretation and comparison of the economic significance of the magnitude of the effects depicted in Figure 2. Moreover, by calculating the tariff-equivalent effect of a standardized shock size at values that relate to the sample distribution, Figure 3 provides insight into the variation in the effects across countries due to differences in underlying climate

Figure 3: Tariff-equivalent effects for sample countries



Notes: This chart depicts the (ad valorem) tariff-equivalent effects of a 1 standard deviation increase in the weather variables. Each point represents the estimated effect for a single sample country, and effects are calculated at the sample mean for that country and the 1 standard deviation increase is also specific to that country. The box plots depict the distribution of these estimated effects across the sample countries. Tariff-equivalent effects calculated using -5 for the trade elasticity of substitution. See section 6.A in the appendix for details on how tariff-equivalent effects are calculated.

conditions. Each point in the figure represents the estimated tariff-equivalent effect for a single country. The box plots show the mean and interquartile range of the tariff equivalent effects across sample countries.

As expected following the results in Figure 2, for manufacturing exports the weather shocks that tend to lead to non-zero tariff-equivalent effects are increases in extreme heat days and annual precipitation. Interestingly, while Panel C suggests that the magnitude of the effect of extreme heat days could become quite large for large increases in the number of extreme heat days, Figure 3 reveals that due to relatively limited within-country variation in extreme heat days, the historical tariff-equivalent effect a 1 standard deviation increase from the mean is just 0.4% on average across sample countries. These estimates suggest that for shocks within the distribution of weather realizations that countries have seen over the past 30 years or so, increases in extreme heat days have positive but fairly small impacts on manufacturing exports. Similarly, while the predicted tariff-equivalent effect of a 1 standard deviation increase from the mean of annual precipitation is statistically significant for all sample countries, the effects are fairly small: the average tariff-equivalent effect is 0.7%.

For the Agriculture sector, Figure 3 reveals a relatively large degree of variation in the tariff-equivalent effects both across countries and across types of weather shocks compared to the Manufacturing sector. The tariff-equivalent effect of a 1 standard deviation increase from the mean is on average 0.9% and 0.4% for annual mean temperature and temperature variance, respectively. The distribution of these effects is also fairly narrow, suggesting that shocks within the within-country climatic variation over the sample period do not lead to positive but modest shifts on barriers to exporting in the agricultural sector. Meanwhile, the tariff-equivalent effects of increases in monthly rainfall deviations are relatively large: they average 2.7% across sample countries. On the other hand, increases in total annual precipitation and in extreme daily rainfall lead to on average small but *negative* tariff-equivalent effects, implying that exporting agricultural products becomes "easier" in response to these types of shocks. On average across sample countries, the tariff-equivalent effects are -1% and -0.5% for annual precipitation and extreme daily rainfall, respectively.

Overall, the tariff-equivalent effects reinforce the result that agriculture exports are more sensitive to weather shocks than international trade. Moreover, the magnitude of these effects are within +/- 5% for all except a small handful of outliers, suggesting that within the scope of weather realizations over the past 30 years or so, weather shocks can have a modest but economically significant impacts on the flow of goods to export markets. As climate change progresses and countries potentially experience shocks greater than the 1 standard deviation of historical weather realizations used to calculate these effects, these predicted tariff-equivalent effects could become larger than the effects depicted in Figure 3, depending on the extent of adaptation that occurs.

4.3 Heterogeneity

This section explores heterogeneity in the effect of weather on exports relative to domestic sales. To do so, I interact the temperature and precipitation functions in Equation 2 with several variables that may be an important source of heterogeneity in the effect of weather shocks on exports relative to domestic sales. I focus on two exporter characteristics and three bilateral variables as these potential sources of heterogeneity. First, given previous evidence that poor countries may be particularly vulnerable to weather shocks (Dell et al. 2012), I test for heterogeneity based on whether the exporter is a low income country[7]. Second, given Beverelli et al. (2018)'s findings that weak institutions decrease exports relative to domestic sales, I also test for heterogeneity based on whether the exporter has weak institutions[8]. Next, given that the results in the previous section suggest that weather shocks exacerbate the trade barrier of an international border, I also test for heterogeneity in the effect based on the presence of other bilateral trade barriers. Specifically, I test for heterogeneity based on whether the exporter and importer have a Regional Trade Agreement (RTA), whether the exporter and importer are relatively far away from each other in terms of geographical distance[9], and whether they share a border. In the results shown below, I focus on exploring heterogeneity in the effects for which exports decrease relative to domestic sales, since these effects have potentially concerning economic implications for both the exporter and their trade partners. Overall, I do not find strong evidence that sensitivity of exports to weather shocks is associated with particular exporter characteristics, but I do find that this sensitivity of exports to weather is stronger when trading partners have larger existing trade frictions, suggesting that weather shocks exacerbate existing trade barriers beyond simply the presence of an international border.

Figure 4 illustrates the results of this heterogeneity analysis, comparing the effect of a 1 standard deviation shock from the sample mean of the weather variable on exports relative to domestic sales, for trade flows with the heterogeneity variable of interest versus those without. Panel A depicts results for the agriculture sector and Panel B shows results for the manufacturing sector. In contrast to previous climate impact studies, I do not find robust evidence that income levels are a notable source of heterogeneity in the effect of weather shocks. Manufacturing exports decrease more in response to an increase in total annual precipitation in low income countries compared to high income countries, but otherwise I find no statistically significant difference in the sensitivity of exports to weather shocks based on countries' income levels. Meanwhile, exports from countries with weak institutions may be more sensitive to weather shocks than domestic sales, particularly in the manufacturing sector. The effect of a 1 standard deviation increase from the sample mean of 1.18 metres of total annual precipitation leads to a -1.7 percentage point difference in the semi-elasticity of exports relative to domestic sales amongst countries with strong institutions, but for countries with weak institutions this difference in the semi-elasticity of exports versus domestic sales increases to -41.2 percentage points, suggesting that weak institutions can play a large role in the sensitivity of exports to precipitation shocks. Nevertheless, this result is not consistent across all effects; for the sensitivity of agricultural exports to an increase in monthly rainfall compared to the climatic norm, exporters with weak institutions are actually less vulnerable to these impacts than exporters with strong institutions. These results provide further evidence beyond those presented in the previous section that the response of exports to weather shocks varies notably between the agriculture and manufacturing sectors. In particular, the institutional quality and potentially the income level of the exporter seems to be more important in these impacts for the manufacturing sector than the agriculture sector.

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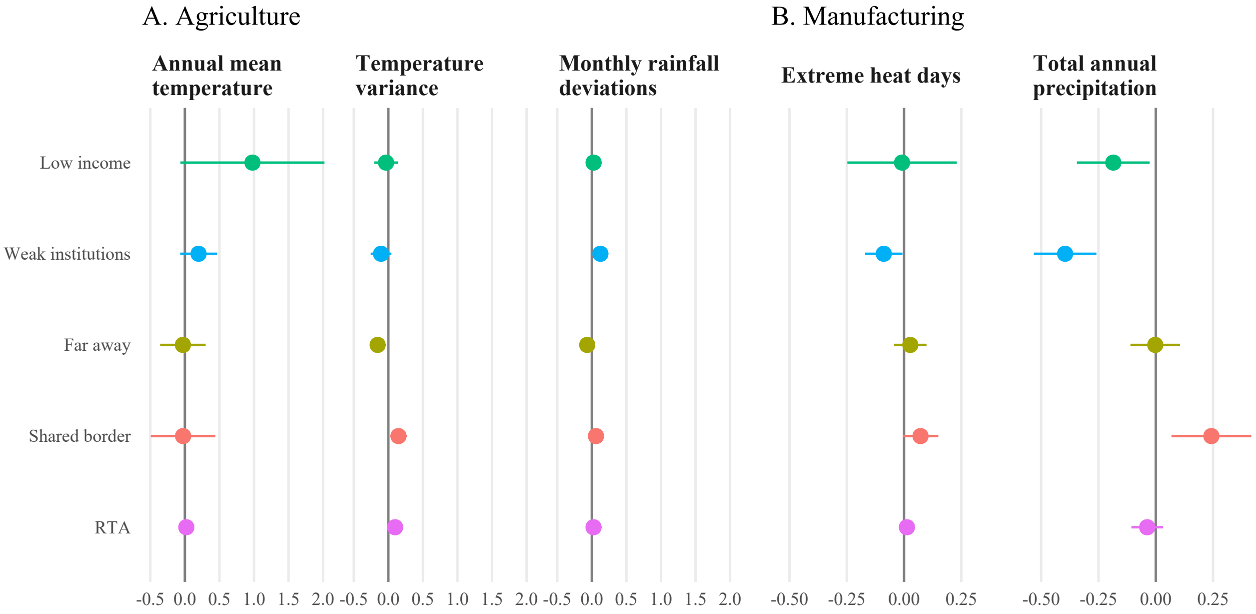
[7] The "Low income" dummy takes a value of 1 when a country is classified as 'Low income' or "Lower middle income" by the World Bank in a given sample year.

[8] The "Weak institutions" dummy takes a value of 1 when a country is below the median observed value of institutional quality index in a given year. See section 3 for a description of this index.

[9] The "Far away" dummy takes a value of 1 if the natural log of the population-weighted geographical distance between the exporter and importer is above the median of all bilateral distances in the sample of exporters and importers.

Figure 4: Heterogeneity in the effect of a 1 standard deviation shock on exports relative to domestic sales



Notes: This plot depicts the difference in the effect of a 1 standard deviation shock from the sample mean of the weather variable on exports relative to domestic sales, for trade flows with the characteristic on the y-axis relative to those without. The error bars represent 95% confidence intervals. "Low income" and "Weak institutions" refer to characteristics of the exporter, while the rest of the variables refer to the exporter-importer pair.

Next, the results depicted in Figure 4 also provide some suggestive evidence of the role that bilateral trade barriers may play in the impact of weather shocks on exports relative to domestic sales. Amongst the bilateral characteristics assessed, the most consistent source of heterogeneity in the effect of weather shocks is whether or not the importer or exporter share a border. For all but the impact of annual mean temperature on agricultural exports, trade flows are less sensitive to weather shocks in the exporting country if trade partners share a border than if they do not. While the results in the previous section suggest that trade flows can be more sensitive to weather shocks if they need to cross an international border compared to if they stay within the same country, these results imply that this sensitivity is even greater if the trade flows must cross multiple international borders or a large body of water. Taken together, these results suggest that importers that have relatively high trade barriers with a given exporting country may be more impacted by weather shocks in that exporting country than importers with relatively low trade barriers. The results for the roles of geographical distance and RTAs on the effects of weather shocks on exports show some support for this hypothesis, although the results are not as strong and consistent as for sharing a border. For the manufacturing sector, trading partners being relatively far away from each other or having an RTA do not have a statistically significant impact on the sensitivity of exports to extreme heat days or total annual precipitation. However, for the agriculture sector, trade flows between countries that are relatively close to each other or that have an RTA are less sensitive to increases in temperature variance or monthly rainfall deviations in the exporting country compared to trade flows between countries that are relatively far away from each other or that do not have an RTA. These results lend further credence to the idea that weather shocks can exacerbate existing trade barriers.

Overall, I find some evidence that the sensitivity of exports to weather shocks that I uncovered in the previous section may be larger when existing trade barriers are large. The results are not consistent across all types of trade barriers and weather shocks, with notable differences once again between the agriculture and manufacturing sectors, but the most notable pattern that emerges from the heterogeneity analysis is consistent with the idea that importing countries are most vulnerable to weather shocks in their trading partner countries if their ties to these countries are relatively weak. In other words, weather shocks may interact with existing disadvantages and exacerbate weaknesses in a country's connections to the global market.

5 Conclusion

This paper uses an approach that brings together developments from previous contributions in international trade and climate econometrics to investigate the differential impact of weather shocks on exports relative to domestic sales, shedding light on the interaction of weather shocks with barriers to international trade. I specifically test for and quantify the particularly sensitivity of exports to weather shocks compared to domestic sales, providing evidence that weather shocks can exacerbate existing trade barriers by causing a decrease in exports relative to domestic sales. Moreover, the empirical model includes a robust set of controls for other factors affecting trade barriers and productivity, enabling me to isolate effects of weather shocks on the flow of trade from effects on productivity.

The results suggest that both manufacturing and agricultural exports are sensitive to weather shocks, but in notably different ways. Manufacturing sector exports are relatively resilient but see small decreases relative to domestic sales in response to increases in extreme heat days and total annual precipitation. Agricultural exports are relatively more sensitive to a more broad set of weather shocks, particularly increases annual mean temperature and temperature variance as well as increases in monthly rainfall relative to the climatic norm. These results suggest that these weather shocks exacerbate the existing trade barrier of an international trade barrier, leading to a decrease in the share of production flowing to export markets relative to domestic markets. The mechanism driving these effects could include an increase in exporters' 'home bias', a change in the relative price of exports, or physical disruptions at ports, rails, and other infrastructure important for sending goods to international markets.

While I do not find strong evidence of heterogeneity in this effect based on the income level or quality of institutions in the exporting country, I do find some evidence that suggests that these effects may be larger when existing barriers to trade are relatively large. In particular, these sensitivity of exports to weather shocks seems to be larger when trading partners do not share a border and to some extent when they are relatively geographically far away from each other. These results provide further evidence that weather shocks interact with and exacerbate existing trade barriers, and suggest that the buyers that are most vulnerable to indirect shocks via weather shocks up the supply chain are those that already face relatively high trade barriers. In other words, local weather shocks seem to propagate unequally through the international trade network, with existing trade barriers being an important factor driving this inequality.

This paper contributes to our understanding of how to conceptualize the economic impacts of climate and weather. Climate change economists often model the economic damages associated with increased temperatures as part of the production function, which implies that these damages are productivity impacts. Moreover, our understanding of inequalities in the economic impacts of climate change across countries mostly focuses on inequality due to differences in the magnitude of these productivity impacts. A growing body of empirical literature demonstrates that countries experience negative economic impacts not just directly from their own local weather shocks, but also indirectly from weather shocks in their trading partners. This paper contributes to and broadens these insights into the cross-border impacts of weather shocks. In particular, the evidence presented here implies that exports are more sensitive than domestic sales to weather shocks, so that the propagation of weather shocks through international supply chains is not simply a one-to-one propagation of the effect of the shock on productivity; instead trade barriers also play a role in this reverberation of shocks through the trade network, leaving some countries more vulnerable than others.

In light of the result in standard trade models that increased openness to international trade increases aggregate welfare, while increased trade barriers decrease aggregate welfare, these results that weather shocks can exacerbate trade barriers and reduce countries' connections to international markets imply that weather shocks decrease aggregate welfare not only directly through production shocks but also indirectly through changes in trade connections. Of course, the welfare implications of this change in trade barriers may be more complex if we consider the within-country distributional impacts across producers and consumers. The degree to which the burden of the tariff-equivalent effect falls on producers versus consumers is an area of future research. Moreover, given that these effects are identified from weather shocks, the economic significance of these results for long-term climate change must be interpreted with caution and remains an area of ongoing research in the field of climate econometrics.

Finally, some policy takeaways arise from this paper. The results confirm findings in many other papers that the agricultural sector is particularly sensitive to weather shocks, and so climate and trade policy should take into account these sector-specific vulnerabilities. In particular, the results stress the importance of policy alignment. Climate and trade interact with each other in their effects on economic welfare, and so climate and trade policy should not exist in silos but instead take into account these interactions. For example, policy initiatives to support trade openness and export-driven growth may benefit from including climate change adaptation measures.

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6 Appendix

6.A Tariff-equivalent effects

As discussed in section 2.3, the marginal effects of interest in this study represent the difference in the semi-elasticity of bilateral trade for exports relative to domestic sales due to a one unit change in the weather variable of interest (e.g. annual mean temperature). Let ρ_w represent this difference in the semi-elasticity associated with weather variable w: $\rho_w = \frac{\partial ln(X_{ij,t})}{\partial w_{i,t}}$. It is the difference (in percentage points) in the effect of a one unit increase in w on exports relative to domestic sales. Let β_τ represent the elasticity of bilateral trade with respect to $1+\tau$, where τ is the ad valorem tariff rate. Therefore $\beta_\tau ln(1+\tau)$ is the percentage change in bilateral trade associated with an ad valorem tariff rate of τ. To obtain the tariff rate that is equivalent to the impact of weather variable w, set ρ_w equal to $\beta_\tau ln(1+\tau)$ and solve for τ:

$$\begin{aligned} \beta_\tau ln(1+\tau) &= \rho_w \\ 1+\tau &= exp\left(\frac{\rho_w}{\beta_\tau}\right) \\ \tau &= exp\left(\frac{\rho_w}{\beta_\tau}\right) - 1 \end{aligned}$$

In the absence of comprehensive data on ad valorem tariff rate equivalent bilateral trade costs, which would enable me to directly estimate β_τ, I rely on the structural interpretation of this parameter as the trade elasticity of substitution in structural gravity models (Yotov et al. 2016). Following Head and Mayer (2014)'s review of the literature on this parameter, I use their preferred value of $\beta_\tau = -5$ in my calculations of tariff-equivalent effects.

6.B Additional tables and figures

Table 3: Stationarity tests for temperature and precipitation variables

	Test statistic	P-value
IPS test with zero lags and a time trend		
Annual mean temperature	-28.478	≤ 0.01
Total annual precipitation	-30.881	≤ 0.01
Cross-sectionally-augmented IPS test with 2 lags and time trend		
Annual mean temperature	-3.06	≤ 0.01
Total annual precipitation	-3.214	≤ 0.01

Notes: "IPS" refers to the Im, Pesaran, Shin test. The null hypothesis for both versions of this test is that the variable is non-stationary. For both the temperature and precipitation variables this null hypothesis is rejected at conventional levels.