



Temperature Variability and the Macroeconomy: A World Tour

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Abstract

This paper uses historical monthly temperature level data for a panel of 114 countries to identify the effects of within year temperature level variability on productivity growth in five different macro regions, i.e., (1) Africa, (2) Asia, (3) Europe, (4) North America and (5) South America. We find two primary results. First, higher intra-annual temperature variability reduces (increases) productivity in Europe and North America (Asia). Second, higher intra-annual temperature variability has no significant effects on productivity in Africa and South America. Additional empirical tests indicate also the following: (1) rising intra-annual temperature variability reduces productivity (even though less significantly) in both tropical and non-tropical regions, (2) inter-annual temperature variability reduces (increases) productivity in North America (Europe) and (3) winter and summer inter-annual temperature variability generates a drop in productivity in both Europe and North America. Taken together, these findings indicate that temperature variability shocks tend to have stronger adverse economic effects among richer economies. In a production economy featuring long-run productivity and temperature volatility shocks, we quantify these negative impacts and find welfare losses of 2.9% (1%) in Europe (North America).

Keywords Temperature variability · Productivity growth · “Macro-regions” · Welfare

JEL Classification E32 · R13 · Q50 · Q51 · Q54

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1 Introduction

Climate change and its potential impact on the real economic activity is still at the center of the academic and policy debate in many economies. Over the last decades, the number of weather- and climate-related events (i.e., drought, extreme temperature, floods, landslides and wildfires) has increased significantly. For instance, as a consequence of global warming, over the period 1990–2019, the world has recorded an average annual increase of 26% and 36% in the number of extreme temperatures and wildfires, respectively. Due to increasing annual precipitation levels, also the number of floods and landslides has strongly increased over the same period (i.e., 6% and 20%, respectively).¹ On the one hand, climate-related events had a devastating impact in terms of human life losses. On the other hand, they have also been responsible for a severe destruction of physical capital with non-negligible economic costs. For instance, over the period 1990–2017, global disaster losses from weather- and climate-related events accounted for 0.22% of global GDP (Pielke 2019). But even more interestingly, over this period weather-related losses (measured in constant 2017 US\$) increased by 74%.

As of today, there are thus no doubts that climate change has affected the weather dynamics and climate systems of many regions around the world. However, the effects of climate change are not homogeneous across countries/regions (see, among others, Dell et al. 2012; Brenner and Lee 2014; Colacito et al. 2019). For instance, in continental regions, climate change has led to an increase in heat extremes, a decrease in summer precipitation and an increasing risk of river floods and forest fires. In coastal zones and regional seas, climate change has been responsible for the rise in sea levels, the increase in sea surface temperatures, the increase in ocean acidity, the northward migration of marine species and the decrease in opportunities for fisheries. As a consequence of climate change, in the Atlantic region instead, more frequent heavy precipitations, rises in river flow, increasing risk of river and coastal flooding, increasing damage risk from winter storms and a decrease in energy demand for heating have been observed. Overall, in terms of economic costs, existing empirical findings have shown that low-income countries tend to be more vulnerable than high-income countries to climate change (see, among others, Dell et al. 2012).

Numbers at the global level indicate the presence of severe adverse economic effects induced by climate change. Nevertheless, climate change may come with both bad and good news depending on the region/country. The net effect of climate change in each region/country depends of course on many factors. Due to its global coverage, a large part of the literature on the economic effects of climate change has focused on the potential impact of global warming on world GDP. Estimates on potential losses on GDP due to higher global temperature levels have been obtained by means of the so-called Integrated Assessment Models (IAMs). However, IAMs have been largely criticized, in particular for being distant from empirically observed temperature and macroeconomic dynamics (see, among others, Pindyck 2013; Revesz et al. 2014; Donadelli et al. 2017).

A first attempt to estimate the true economic effects of climate change is provided by Dell et al. (2012) who use countries' historical temperature fluctuations to identify their effects on aggregate economic outcomes (i.e., output level and output growth). Dell et al. (2012) find that rising temperature levels have significant adverse effects on economic

¹ Source: <https://www.emdat.be/>.

growth only in poor countries.² In the spirit of Dell et al. (2012), using a panel of 105 countries, Brenner and Lee (2014) examine whether temperature and precipitation level shifts are associated with decreases in economic growth. They find negative effects of rising temperatures on economic growth in warm and developed countries whereas increases in precipitation generate positive effects on growth, especially in developed countries with low average precipitation. Focusing on the US, Colacito et al. (2019) document a decrease in output and productivity growth following an increase in average summer temperature, pointing out the importance of seasonal effects. Moreover, they show that the negative effect of rising summer temperatures on output growth is stronger for the southern region.³ Zhao et al. (2018) argue that the effects of annual temperature on productivity can also vary greatly across space within countries. They revisit the temperature-economic growth relationship using global sub-national short panel data and show that climate adverse effects can vary at the regional level. Lanzafame (2014) re-examine the effects of temperature and rainfall on economic growth in Africa. A significant evidence of short- and long-run relations between temperature and economic growth is found. Rainfall, however, is found to have only marginal effects on economic growth.

While many studies have reported associations between short-term (or long-term) temperature changes and economic growth, evidence on the relationship between within-year temperature variability (i.e., temperature volatility) and macroeconomic aggregates is scarce.⁴ Some studies, however, indicate that variability in climate change phenomena (e.g., temperature and precipitation levels) may also have significant adverse effects on economic development. Wheeler et al. (2000) provide evidence of the importance of variability in temperature, independent of any substantial changes in mean seasonal temperature, for the yield of annual crops. For instance, Dee et al. (2016) find that within-year temperature variability has a negative impact on regional fisheries yields.

In this paper, we account for this important feature of climate change and examine the macroeconomic impact of variability in temperature levels. In particular, we capture variability in temperature levels around the world by building a measure of intra-annual temperature volatility for a panel of 114 countries. We then investigate the impact of unexpected changes in temperature variability on productivity growth in five different “macro-regions”, i.e., (1) Africa, (2) Asia, (3) Europe, (4) North America and (v) South America. Using standard Panel VAR models, we provide novel evidence on the impact of intra-annual variability in temperature levels on the macroeconomy. Surprisingly, we find that an intra-annual temperature volatility shock produces adverse effects on aggregate productivity in more developed regions (i.e., Europe and North America). In contrast, there are no significant evidence of temperature variability affecting productivity growth in South America and Africa. Unexpected changes in intra-annual temperature volatility come instead with good news in Asia. We perform additional empirical tests and find the following: (1) tropical and not-tropical regions are both adversely affected by intra-annual temperature volatility shocks, (2) inter-annual temperature volatility (captured by the standard deviation

² As opposed to IAMs which, for decades, focused on the impact of rising temperatures on the level of GDP, Dell et al. (2012) find in their empirical study that higher temperatures may also reduce growth rates of output.

³ Donadelli et al. (2017) also examine the effect of temperature level shocks on aggregated productivity in the US. By means of VAR analyses, they empirically show that a temperature level shock has a sizable, negative and statistically significant impact on the growth rate of TFP, output, and labor productivity.

⁴ Throughout the paper the term “temperature variability” and “temperature volatility” will be used interchangeably.

computed using a rolling window of 10 years of average annual temperature level data for each country) affects regions around the world differently leading to a drop (rise) in aggregated productivity in North America and South America (Africa, Asia and Europe), (3) stronger inter-annual temperature variability in the winter and summer seasons is detrimental for productivity both in Europe and North America whereas spring and fall inter-annual temperature variability boosts European productivity and (4) a standard fixed effects panel regression confirm productivity in Europe and North America to be negatively affected by intra-annual temperature volatility shocks.⁵

To gain more quantitative insights on the short- and long-term implications of climate change variability on growth and welfare, we provide a general equilibrium model that accounts for the adverse effects of temperature volatility on aggregate productivity and output growth, as observed in Europe and North America. In the model, which accounts for the dynamics of both macroeconomic aggregates and asset prices, the implied drop in aggregate productivity observed in Europe (North America) generates losses in lifetime utility of 2.9% (1.0%).

In sum, the contribution of this study is threefold. First, we build a novel proxy of climate change variability (i.e., intra-annual temperature volatility) for 114 countries. Second, we provide novel insights on the interplay between climate change variability and economic growth. Importantly, we show that intra-annual temperature volatility shocks reduce productivity growth in rich economies while having only mild effects in developing/poor economies. Broadly, our evidence seem to be at odd with existing empirical findings on the implications of global warming indicating that rising temperature levels tend to reduce economic growth in poor countries (Mendelsohn et al. 2006; Dell et al. 2012). Third, we provide a suitable theoretical framework to quantify the welfare costs induced by the drops in aggregate productivity generated by a stronger temperature variability in Europe and North America.

The rest of the paper is structured as follows: in Sect. 2, we present a brief overview of the literature, in Sect. 3, we empirically investigate the importance of rising temperature variability, in Sect. 4 we set up a model and quantify the welfare costs of increasing temperature variability. Finally, Sect. 5 offers some concluding remarks.

2 Literature Discussion

Broadly, this paper is intended as a contribution to the growing literature examining the links between climate change and macroeconomic and financial dynamics. For the sake of brevity, only those papers most closely related to ours will be discussed, beginning with Donadelli et al. (2020).

The work of Donadelli et al. (2020) represents a first attempt to examine the effects of temperature volatility on macroeconomic aggregates and asset prices. By relying on two centuries of UK data the authors provide evidence of temperature volatility shocks undermining productivity in the post-war period (i.e., 1950–2015). In a temperature-augmented long-run productivity risk model, they then show that temperature volatility shocks generate sizable welfare costs. We complement and improve their empirical analysis by focusing

⁵ Brenner and Lee (2014) also observe negative macroeconomic implications of climate change in developed economies.

on a panel of 114 countries and estimating the effects of intra-annual as well as inter-annual temperature volatility shocks on aggregate productivity in different world macro-regions. Importantly, this allows us to check whether climate change variability effects are homogeneous around the world.

From the empirical side, our paper is then very close to Dell et al. (2012) who examine the historical relationship between changes in a country's temperature and precipitation levels and changes in its economic performance. Differently from a variety of existing empirical analyses that focus on a single country, Dell et al. (2012) use a panel of 125 countries. Their empirical findings indicate that rising temperature levels reduce economic growth in poor countries. Moreover, temperature level shocks reduce the growth rate of output and not just its level. We differ from them in two main aspects. First, we focus on the macroeconomic implications of intra-annual temperature variability, as measured by the standard deviation of monthly temperatures within each year. We therefore assign greater importance to unexpected shifts in monthly temperature levels within a year, which in our opinion can generate severe effects on a variety of sectoral activities as well as on households' consumption plan. Second, we provide a model that quantitatively accounts for the adverse effects of temperature volatility on productivity and output growth observed in the data.

Our empirical investigation is also related to the literature on climate change finance and in particular to all those works aimed at examining the effects of climate change dynamics on stock market returns. For instance, supporting empirical evidence of drops in aggregate asset prices due to rising temperature levels can be found in Bansal and Ochoa (2011) and Donadelli et al. (2017). Balvers et al. (2017) find also that temperature shocks (on average) generate a increase in the cost of capital. Focusing on all companies listed in the STOXX Europe 600 Index, Tzouvanas et al. (2019) observe that higher temperatures are highly detrimental for the financial system. In particular, hot temperature shocks are found to be responsible for a significant increase in systemic risk. Novy-Marx (2014) finds instead that global warming (among other interesting variables) has the power of predicting the performance of some of the best known financial market anomalies. Rather than focusing on temperature level shifts, in this study only temperature variability/volatility shocks are considered as potential drivers of asset prices.

Finally, we are more distantly related to all those works integrating the climate science and economic aspects of the impact of greenhouse emissions or rising temperature levels (i.e., IAMs). However, IAMs lack important theoretical and empirical foundations (see, among others, Pindyck 2012). Moreover, so far, exclusively effects on GDP levels have been exploited leaving out implications for investment, capital, labor productivity and welfare (see Revesz et al. 2014). Our theoretical framework, instead, accounts for the negative effects of intra-annual temperature variability on aggregate productivity growth in Europe and North America, as indicated by temperature and macro data. Moreover, the associated welfare costs are computed from a model that also matches main business cycle and asset price dynamics.

3 Empirical Analysis

3.1 Data

Our empirical analysis employs data for more than 100 countries, which have been grouped in five different macro-regions: (1) Africa, (2) Asia, (3) Europe, (4) North America and (5) South America⁶

3.1.1 Temperature

Our measure of annual temperature volatility, $\sigma(T)$, is computed (for each country) using monthly mean temperature levels retrieved from the Climate Change Knowledge Portal (CCKP) of the World Bank. Precisely, it is defined as the absolute value of the difference between the intra-annual temperature volatility estimated in each year t and the average intra-annual temperature volatility computed over the base period 1900–1950.⁷ Formally,

$$\sigma(T)_t = |\sigma(\text{Jan} - \text{Dec})_t - \bar{\sigma}(\text{Jan} - \text{Dec})_{1900-1950}|,$$

where $\sigma(\text{Jan} - \text{Dec})_t$ is the standard deviation computed using January–December monthly temperature observations for each year t and $\bar{\sigma}(\text{Jan} - \text{Dec})_{1900-1950}$ is the average of $\sigma(\text{Jan} - \text{Dec})_t$, computed over the period 1900–1950. Note that the absolute value ensures that both positive and negative deviations in temperature volatility can be harmful for growth and productivity. In practice, our measure allows to capture the potential negative effects of (1) years with a relatively high degree of variation in intra-annual temperature levels and (2) years with little movements in monthly temperatures. Needless to say, large within year temperature variations can have severe implications for productivity in agriculture and fishery activities and can be responsible for extreme weather events (e.g., heavy rain, floods and landslides). On the other hand, a year with little variations in monthly temperature level can be characterized by prolonged heat or cold waves. Of course, also these scenarios can be harmful for some sectors (e.g., agriculture, forestry, fishery and energy and water supply) and generate extreme weather (e.g., drought and wildfires, tornadoes and hurricanes).

3.1.2 Macroeconomic Variables

Data on productivity (TFP), aggregate output (GDP), and physical capital have been retrieved from the Penn World Table (version 9.1). Precisely, we use TFP at constant national prices (2011 = 1) and real GDP and capital stock at constant 2011 national prices (in mil. 2011US\$).

Main descriptive statistics on countries' temperature data (i.e., average temperature level and intra-annual temperature volatility for the period 1950–2016) are reported in Table 1.⁸ In Fig. 1 we instead plot for each country the average temperature level (Panel A)

⁶ GDP data is available for 169 countries while TFP data is available for 114 countries.

⁷ In a robustness test, we build an inter-annual temperature volatility measure. This is represented by the standard deviation—computed using a rolling window of 10 years—of annual temperature levels.

⁸ Note, that some countries (e.g., Russia) are included in more than one region when the country crosses borders of continents.

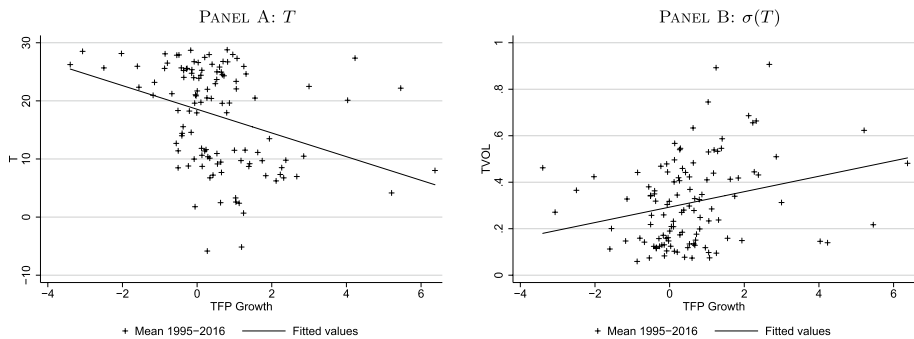
Table 1 Summary statistics: average temperature level and temperature volatility (1950–2016)

Africa			Asia			Europe			North America			South America		
ISO	<i>T</i>	$\sigma(T)$	ISO	<i>T</i>	$\sigma(T)$	ISO	<i>T</i>	$\sigma(T)$	ISO	<i>T</i>	$\sigma(T)$	ISO	<i>T</i>	$\sigma(T)$
AGO*	21.7	0.17	ARE	27.2	0.27	ALB	11.7	0.41	ATG*	25.7	0.11	ARG	14.4	0.26
BDI*	20.4	0.18	ARM	7.4	0.49	ARM	7.4	0.49	BHS*	25.0	0.28	BOL*	20.9	0.16
BEN*	27.6	0.15	AZE	12.0	0.47	AUT	6.6	0.46	BLZ*	25.3	0.15	BRA*	25.1	0.08
BFA*	28.4	0.21	BGD*	25.2	0.20	AZE	12.0	0.47	BRB*	26.3	0.11	CHL	8.3	0.18
BWA	21.8	0.21	BHR	27.4	0.36	BEL	9.9	0.47	CAN	-6.6	0.48	COL*	24.5	0.12
CAF*	25.1	0.15	BRN*	25.5	0.07	BGR	10.9	0.44	CRI*	24.6	0.14	ECU*	21.5	0.16
CIV*	26.5	0.13	BTN	12.0	0.21	BIH	9.9	0.48	DMA*	24.5	0.11	PER*	19.5	0.18
CMR*	24.7	0.15	CHN	6.6	0.32	BLR	6.7	0.74	DOM*	24.1	0.12	PRY*	23.6	0.33
COD	24.2	0.08	CYP	19.1	0.32	CHE	6.1	0.45	GRD*	26.8	0.11	SUR*	25.9	0.11
COG	24.7	0.11	GEO	6.6	0.47	CYP	19.1	0.32	GTM*	23.5	0.14	URY	17.7	0.32
COM*	25.5	0.12	IDN*	26.0	0.07	CZE	8.2	0.49	HND*	23.7	0.12	VEN*	25.6	0.11
CPV	23.1	0.29	IND*	24.3	0.20	DEU	8.8	0.48	HTI*	24.7	0.12			
DJI*	27.9	0.18	IRN	17.2	0.38	DNK	8.1	0.54	JAM*	25.2	0.13			
DZA	22.9	0.26	IRQ	21.8	0.34	ESP	13.4	0.28	KNA*	24.8	0.11			
EGY	22.5	0.29	ISR	19.7	0.27	EST	5.5	0.75	LCA*	25.9	0.10			
ETH*	22.8	0.14	JOR	18.9	0.27	FIN	1.7	0.77	MEX*	20.8	0.16			
GAB*	25.1	0.13	JPN	10.8	0.36	FRA	11.0	0.41	NIC*	24.9	0.12			
GHA*	27.4	0.12	KAZ	6.1	0.80	GBR	8.6	0.34	PAN*	25.3	0.12			
GIN*	25.9	0.15	KGZ	2.5	0.65	GEO	6.6	0.47	SLV*	24.0	0.14			
GMB*	27.5	0.17	KHM*	27.1	0.23	GRC	14.0	0.34	TTO*	26.3	0.12			
GNB*	27.0	0.16	KOR	11.0	0.45	HRV	10.8	0.47	USA	7.2	0.26			
GNQ*	24.7	0.12	KWT	25.5	0.38	HUN	10.3	0.52	VCT*	27.0	0.10			
KEN*	24.7	0.12	LAO*	23.5	0.24	IRL	9.4	0.31						
LBR*	25.5	0.14	LBN	16.1	0.29	ISL	1.9	0.32						
LSO	13.1	0.18	LKA*	26.9	0.07	ITA	12.1	0.36						
MAR	17.7	0.28	MDV	27.8	0.11	KAZ	6.1	0.80						
MDG*	22.3	0.12	MMR	23.0	0.15	LTU	6.6	0.70						
MLI*	28.5	0.29	MNG	-0.2	0.81	LUX	9.3	0.47						
MOZ*	23.9	0.18	MYS*	25.4	0.07	LVA	6.0	0.72						
MRT*	27.9	0.23	NPL	12.3	0.30	MDA	9.9	0.66						
MUS*	22.9	0.12	OMN	25.7	0.19	MKD	10.1	0.41						
MWI*	22.1	0.19	PAK	20.1	0.33	MLT	18.9	0.31						
NAM	20.4	0.15	PHL*	25.6	0.10	MNE	9.1	0.47						
NER*	27.4	0.30	QAT	27.5	0.35	NLD	9.7	0.50						
NGA*	26.9	0.16	RUS	-6.0	0.48	NOR	1.2	0.58						
RWA*	19.5	0.19	SAU	25.0	0.29	POL	8.1	0.56						
SDN*	27.1	0.25	SGP*	27.3	0.08	PRT	15.1	0.26						
SEN*	28.2	0.18	SYR	18.0	0.32	ROU	9.2	0.57						
SLE*	26.1	0.12	THA*	26.4	0.22	RUS	-6.0	0.48						
STP*	23.7	0.12	TJK	3.5	0.55	SRB	10.5	0.52						
SWZ	20.1	0.19	TKM	15.4	0.57	SVK	7.9	0.53						
SYC*	27.2	0.09	TUR	11.3	0.41	SVN	9.0	0.46						
TCD*	26.9	0.30	UZB	12.5	0.70	SWE	1.9	0.68						

Table 1 (continued)

Africa			Asia			Europe			North America			South America		
ISO	T	$\sigma(T)$	ISO	T	$\sigma(T)$	ISO	T	$\sigma(T)$	ISO	T	$\sigma(T)$	ISO	T	$\sigma(T)$
TGO*	27.1	0.13	VNM*	24.3	0.21	TUR	11.3	0.41						
TUN	19.7	0.33	YEM	23.5	0.14	UKR	8.5	0.71						
TZA*	22.5	0.11												
UGA*	22.9	0.16												
ZAF	17.8	0.15												
ZMB	21.9	0.19												
ZWE	21.5	0.22												

This table reports (for each country) mean values for the annual temperature level and the intra-annual temperature volatility. Countries are grouped in five different “macro-regions”. Note that some countries (e.g., Russia) are included in more than one region when a country crosses different continents. * denotes a tropical country

**Fig. 1** Temperature, temperature volatility, and productivity

and the average intra-annual temperature volatility (Panel B) against the average productivity growth.⁹ The regression lines indicate the presence of a negative relationship between temperature and productivity growth (Panel A) and positive relationship between temperature volatility and productivity growth (Panel B). However, if one ignores the fitting lines, it does not seem that there is a clear-cut link between temperature dynamics and productivity. Looking at different regions separately, the positive relationship between temperature volatility and productivity growth can be observed for Europe, North America, South America, and Asia, while for Africa the regression line predicts a negative relationship (see Fig. 2).¹⁰ These preliminary results suggest that a deeper empirical analysis on the

⁹ Since TFP data for the full period 1950-2016 are not available for all countries, average values have been computed using the sub-period 1995-2016.

¹⁰ Also when plotting the first difference of intra-annual temperature volatility against TFP growth, no clear relationship between productivity and temperature volatility is visible (see Fig. 7). When looking at different regions, results are qualitatively similar for Europe, North America and South America, while the sign of the slope of the regression line changes for Asia and Africa compared to the scatter plot using the level of temperature volatility. Results are not much different when plotting long-run changes in temperature volatility against long-run changes in TFP (see Fig. 8).

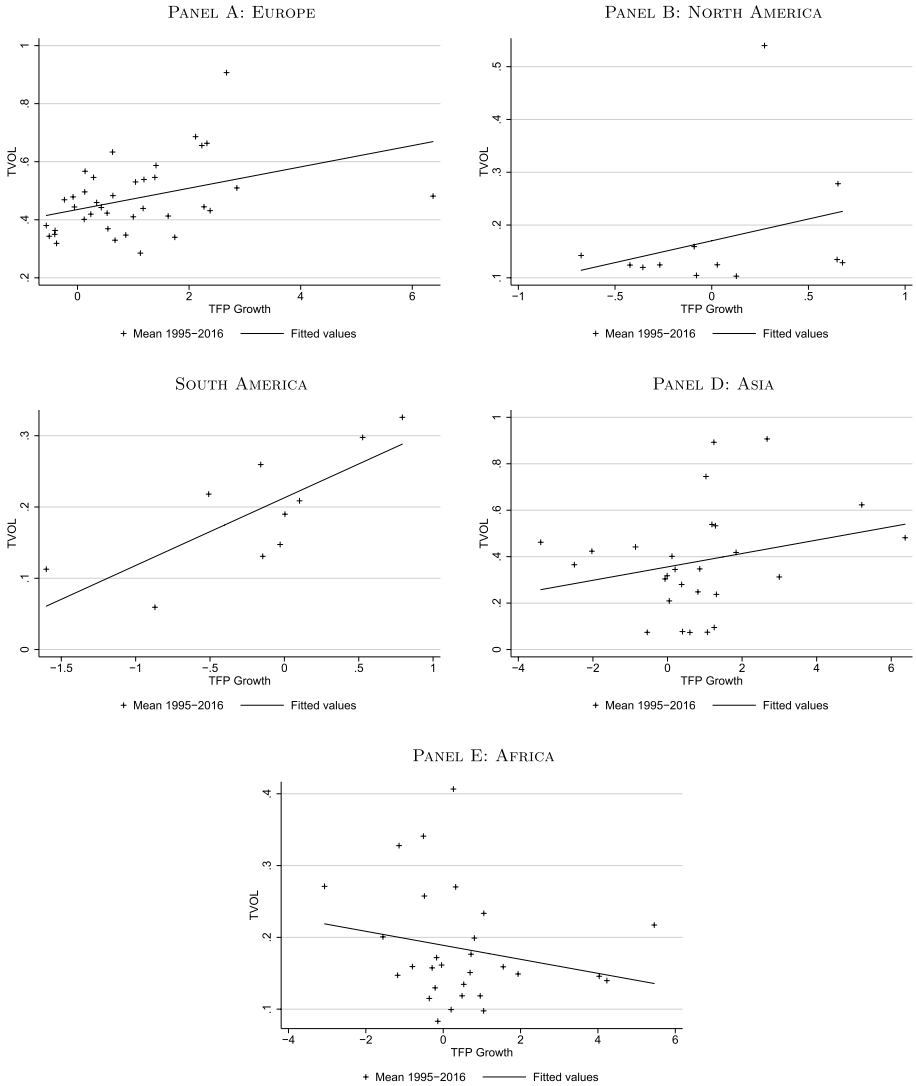


Fig. 2 Temperature, temperature volatility, and productivity (by Region)

temperature variability-growth nexus is needed. In what follows, we perform panel VAR regressions controlling for aggregate economic activity to better examine the implications of stronger temperature variability for aggregate productivity growth.

3.2 Panel VAR Analysis

To analyze the effects of intra-annual temperature volatility on productivity growth, we estimate a panel VAR using the PVAR package provided by Abrigo and Love (2016). Specifically, the homogeneous Panel VAR of order 1 with country-specific fixed effects is represented by the following system of linear equations:

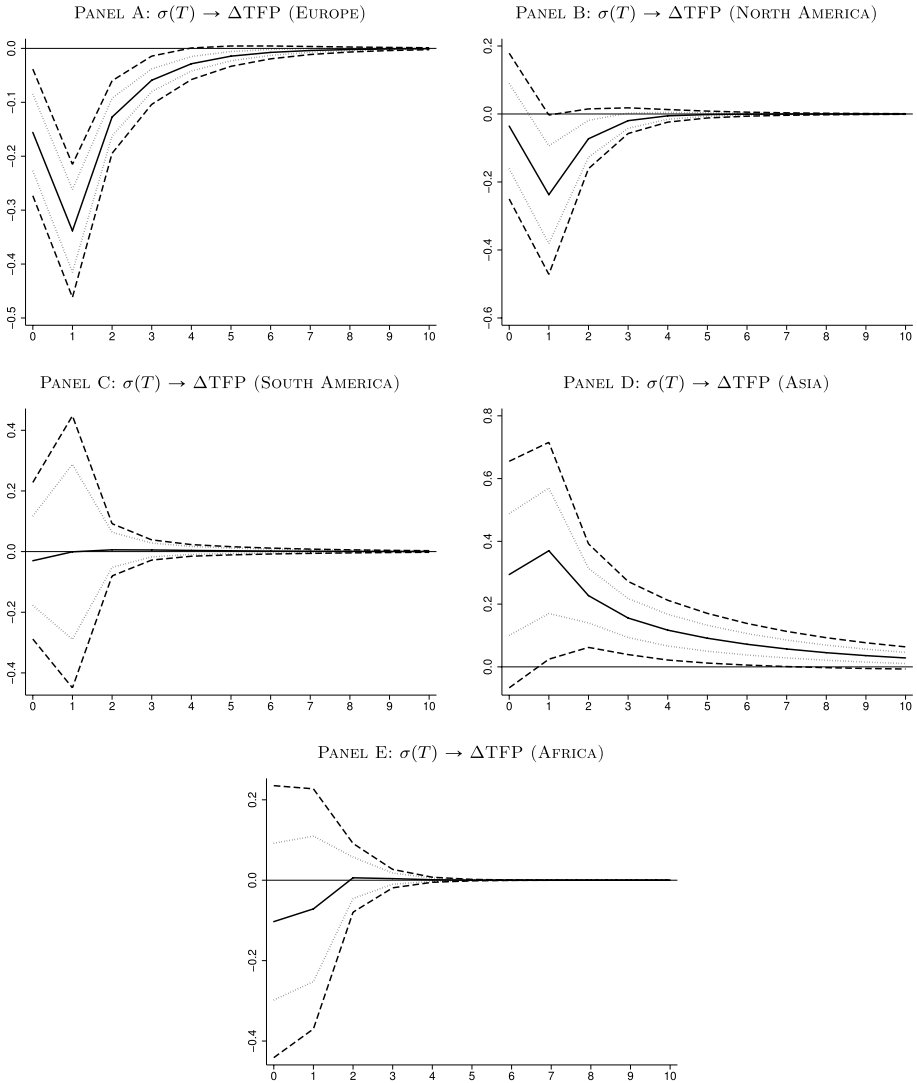


Fig. 3 Impulse Response of TFP Growth to a temp-vol shock in different regions. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

$$Y_{i,t} = A_1 Y_{i,t-1} + u_i + e_{i,t}, \tag{1}$$

where the (1×2) vector of dependent variables $Y_{i,t}$ includes intra-annual temperature volatility, TFP growth, and GDP growth as an additional control variable; u_i and $e_{i,t}$ are (1×2)

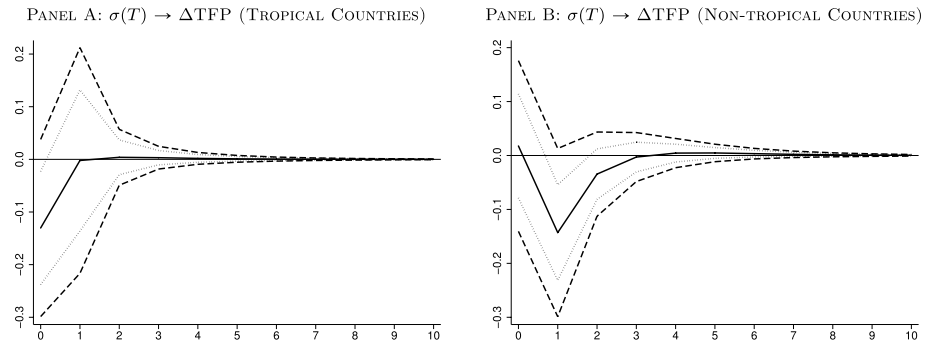


Fig. 4 Impulse Response of TFP Growth to a temp-vol shock: tropical versus non-tropical countries. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

vectors of dependent variable-specific panel fixed-effects and idiosyncratic errors, respectively. The model is estimated by Generalized Method of Moments (GMM), and we use the first four lags of the dependent variables as instruments.¹¹ When computing orthogonalized impulse responses, we assume the following variables ordering: $Y_{i,t} = [\sigma(T), \Delta Y, \Delta TFP]$ (i.e., intra-annual temperature volatility is assumed to be the most exogenous variable)

According to the orthogonalized impulse responses in Fig. 3, an intra-annual temperature volatility shock exerts an adverse (positive) effect on TFP growth for Europe and North America (Asia). Moreover, responses are significant at the 90%-level for Europe and Asia and significant at the 68%-level for North America. For South America and Africa, there is no clear evidence is found on the impact of temperature volatility shocks on TFP growth. Taken together, our novel empirical evidence suggest that the impact of climate change variability on productivity is not homogeneous across countries. Importantly, it is observed that unexpected and sizable changes in intra-annual temperature levels tend to be more detrimental in those countries exhibiting a higher degree of urbanization (see also, Donadelli et al. 2020).

Additional empirical tests As a first robustness test, we decide to divide the sample into tropical countries versus non-tropical countries and analyze whether intra-annual temperature volatility effects are different among these two country groups. Results from Fig. 4 indicate that productivity in both tropical and non-tropical countries is negatively affected (at 68% level) by intra-annual temperature volatility shocks. However, the response seems

¹¹ Panel models have the same structure as VAR models but add a cross-sectional dimension. Specifically, Panel VARs allow for country-level heterogeneity and more degrees of freedom. Additionally, panel VARs have an advantage over standard panel models in that all variables are assumed to be endogenous and interdependent.

to be immediate and short-lived for tropical countries whereas it is lagged and more long-lived for non-tropical countries.

We then test whether our benchmark results in Fig. 3 are robust when an order invariant approach is used (i.e., simple/generalized impulse responses). Impulse responses from this alternative approach are reported in "Appendix" 2 and indicate that main results do not depend on the specific ordering of variables (see Fig. 9). Very similar results are obtained also when controlling for capital instead of GDP in the Panel-VAR (see Fig. 10 in "Appendix" 3). Only one difference is noteworthy: the positive effects of intra-annual temperature volatility on productivity in Asia seem to be less persistent (see Panels D in Figs. 3 and 10).

Instead, in "Appendix" 4, we test whether our results are robust to using an alternative measure of temperature variability. Actually, we use a measure of inter-annual temperature volatility represented by the standard deviation – computed using a rolling window of 10 years – of annual temperature levels ($\sigma(T)_{rw}$). It seems that across regions, changes in inter-annual temperature volatility affects TFP growth differently compared to changes in intra-annual temperature volatility. This is not surprising, since the two measures capture different aspects of temperature variability. In particular, higher within year temperature variability may require faster adaptation than variability in temperature levels over a time span of ten years. Impulse responses in Fig. 11 indicate that inter-annual temperature volatility shocks have a negative (positive) effect on productivity growth in North and South America (Africa and Europe). For Asia, results also point to positive effects but they are less significant. Comparing instead tropical versus non-tropical countries, inter-annual temperature volatility effects on productivity growth are positive for non-tropical countries whereas for tropical countries, effects seem to be negative on impact and positive afterwards (see Fig. 12).

When studying the effects of intra- and inter-annual temperature volatility within the period 1975–2016 using Panel VARs (see "Appendix" 5), results are broadly similar. One main difference is that the negative impact of intra-annual temperature volatility on productivity in North America vanishes (see Figs. 13, 14, 15, 16).

We have also tried to dive deeper into regional effects by looking at different sub-regions. Results for the regions Northern Europe, Central Europe, Middle-East and Sub-Saharan Africa are reported in "Appendix" 6. Results point to negative significant effects of intra-annual temperature volatility on productivity growth in Central Europe while the effect for Northern European countries is less clear. For Middle-East countries the effect is positive and significant while they are negative but not significant in Sub-Saharan Africa (see Fig. 17).

In the spirit of Colacito et al. (2019), we test for seasonal differences in temperature volatility effects on productivity growth (see "Appendix" 7–10). To this end, we recompute the inter-annual temperature volatility index describe above for each season.¹² When breaking down the volatility index on the seasonal level, we encountered stationarity problems in many cases when using the level of the index. Therefore, to be consistent, temperature volatility enters the model as first-difference in all seasonal estimations. Results are reported in Figs. 18, 19, 20, 21. In Europe, inter-annual temperature volatility negatively affects productivity growth in winter and summer with effects in winter being more significant, while

¹² In this respect, we follow Colacito et al. (2019) and define the winter as January through March, the spring as April through June, the summer as July through September, and the fall as October through December. Note that a seasonal intra-annual temperature volatility proxy cannot be computed. This because only monthly temperature level observations are available.

effects are significantly positive in spring and fall. For North America, we find significant negative effects in winter, summer and fall, while effects in spring are significantly positive. For South America, inter-annual temperature volatility effects are significant in winter (negative) and fall (positive). Results for spring also point to negative effects but they are less significant, while results for summer are unclear as the sign of the effect changes in the years following the shock. For Asia we find significant positive effects in winter, while the sign of the effect in other seasons also changes in the years following the shock. For Africa, there does not seem to be much heterogeneity in seasonal effects.

For the sake of completeness, we also estimate a standard fixed effects panel model, regressing (for each region) TFP growth on intra-annual temperature volatility, controlling for GDP growth.¹³ Results also show negative effects of intra-annual temperature volatility on TFP in Europe and North America (see Table 5 in “Appendix” 11). Note that existing empirical findings have shown that temperature level shocks tend to reduce economic growth only in poor countries (see e.g., Dell et al. 2012). Here, effects of shocks to temperature volatility does not seem to affect poor countries more compared to rich countries. In fact, when including an interaction term between intra-annual temperature volatility and a poor county dummy variable (constructed similar to Dell et al. (2012)) in the standard panel model including all countries and regions, results do not show significant differences in temperature volatility effects for poor and rich countries (see Table 5).

4 A Theoretical Framework for Europe and North America

We rationalize the adverse effects of rising temperature volatility observed in Sect. 3 by means of a production economy exhibiting long-run productivity risk à la Croce (2014) and stochastic temperature volatility as in Donadelli et al. (2020). In the model, exogenous processes for temperature level and volatility enter directly into the evolution of aggregate productivity. In particular, temperature dynamics are such that temperature volatility shocks have a negative impact on productivity as indicated by evidence for the regions Europe and North America in Sect. 3.2.

Households Our representative household has Epstein and Zin (1989) preferences defined over consumption and labor:

$$U_t = \left[(1 - \beta) \tilde{C}_t^{1-\frac{1}{\psi}} + \beta \left(\mathbb{E}_t[U_{t+1}^{1-\gamma}] \right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right]^{\frac{1}{1-\frac{1}{\psi}}} \tag{2}$$

where \tilde{C}_t is a Cobb-Douglas aggregator for consumption C_t and leisure $1 - L_t$ taking the following form:

$$\tilde{C}_t \equiv \tilde{C}(C_t, L_t) = C_t^\nu (A_t(1 - L_t))^{1-\nu},$$

with A_t capturing aggregate productivity (i.e., TFP).

The stochastic discount factor (SDF) in this setting is

¹³ In contrast to our benchmark panel-VAR analysis, temperature volatility here is purely exogenous. Alternatively, one may also estimate a panel-VAR model where temperature volatility is included as exogenous variable.

$$M_{t,t+1} = \beta \left(\frac{\tilde{C}_{t+1}}{\tilde{C}_t} \right)^{1-\frac{1}{\psi}} \left(\frac{C_{t+1}}{C_t} \right)^{-1} \left(\frac{U_{t+1}^{1-\gamma}}{\mathbb{E}_t[U_{t+1}^{1-\gamma}]} \right)^{\frac{1/\psi-\gamma}{1-\gamma}}. \quad (3)$$

Firms Final production in the economy is fulfilled by a representative perfectly competitive firm that employs both capital and labor to produce the final output. The aggregate production function is as follows:

$$Y_t = K_t^\alpha (A_t L_t)^{1-\alpha},$$

where α is the capital share and labor L_t is supplied by the household. The aggregate productivity growth rate, $\Delta a_t = \log(A_t/A_{t-1})$, encompasses a long run risk component as in Croce (2014) and time varying volatility of temperature (i.e. stochastic temperature volatility).

The capital stock evolves according to

$$K_{t+1} = (1 - \delta_K)K_t + G\left(\frac{I_t}{K_t}\right)K_t,$$

where δ_K is the depreciation rate of capital. $G(\cdot)$, the function transforming investment into new capital, features convex adjustment costs as in Jermann (1998):

$$G := G\left(\frac{I_t}{K_t}\right) = \frac{\alpha_1}{1 - \frac{1}{\tau}} \left(\frac{I_t}{K_t}\right)^{1-\frac{1}{\tau}} + \alpha_2.$$

Asset prices The intertemporal Euler conditions defining the risk-free rate R_t^f and the return on capital R_t are as follows:

$$\frac{1}{R_t^f} = \mathbb{E}_t[M_{t,t+1}], \quad 1 = \mathbb{E}_t[M_{t,t+1}R_{t+1}],$$

where

$$R_{t+1} = \frac{\frac{\alpha Y_{t+1} - I_{t+1}}{K_{t+1}} + q_{t+1}(G_{t+1} + 1 - \delta_K)}{q_t}.$$

The price of capital q_t is equal to the marginal rate of transformation between new capital and consumption:

$$q_t = \frac{1}{G'\left(\frac{I_t}{K_t}\right)}$$

The unlevered equity risk premium is computed as follows

$$R_{ex,t} = R_t - R_{t-1}^f,$$

where $R_t^f = \frac{1}{\mathbb{E}_t[M_{t,t+1}]}$.

Labor market The optimal solution in the labor market implies that the marginal rate of substitution between consumption and leisure equals the marginal productivity of labor:

$$\frac{1 - \nu}{\nu} \left(\frac{C_t}{1 - L_t} \right) = (1 - \alpha) \frac{Y_t}{L_t}.$$

Productivity and temperature dynamics The following specification for the process of aggregate productivity and temperature allows us to quantitatively examine the link between temperature volatility shocks and the macroeconomy:

$$\begin{aligned} \Delta a_{t+1} &= \mu_a + x_t + x_{t+1}^z + \sigma_a \epsilon_{a,t+1} \\ x_t &= \rho_x x_{t-1} + \sigma_x \epsilon_{x,t} \\ x_{t+1}^z &= \rho_x^z x_t^z + \tau_\theta \sigma_\theta \epsilon_{\theta,t+1} \\ z_{t+1} &= \mu_z + \rho_z (z_t - \mu_z) + e^{\theta_{t+1}} \sigma_z \epsilon_{z,t+1} \\ \theta_{t+1} &= \rho_\theta \theta_t + \sigma_\theta \epsilon_{\theta,t+1} \end{aligned} \tag{4}$$

$$\epsilon_{a,t+1}, \epsilon_{x,t}, \epsilon_{\theta,t+1}, \epsilon_{z,t+1} \sim N \text{ i.i.d.}(0, 1),$$

with the four shocks $\epsilon_{a,t+1}$, $\epsilon_{x,t}$, $\epsilon_{\theta,t+1}$ and $\epsilon_{z,t+1}$ being mutually independent. Eq. (4) indicates thus the presence of both temperature level, $\epsilon_{z,t}$, and temperature volatility shocks, $\epsilon_{\theta,t}$. μ_a and μ_z captures the long-run average of aggregate productivity growth and temperature, respectively. $\epsilon_{a,t}$ represents standard short-run productivity shocks whereas $\epsilon_{x,t}$ refers to the long-run risk component in productivity growth. $\epsilon_{\theta,t}$ is instead intended to capture long-run shocks in stochastic temperature volatility. The persistence of long-run macro and temperature-related productivity shocks is measured by ρ_x and ρ_x^z , respectively.

The shock term $\tau_\theta \sigma_\theta \epsilon_{\theta,t+1}$ attempts to capture the effect of shifts in temperature volatility on productivity growth.¹⁴ While $\sigma_z \epsilon_{z,t+1}$ is the stochastic component of temperature level, the term $e^{\theta_{t+1}}$ represents time-varying volatility of temperature. Broadly, in our theoretical framework θ can be interpreted as a proxy for climate change variability. The parameter τ_θ embedded in x^z captures the direction and the intensity with which temperature volatility shocks impact long-run productivity growth. The parameter τ_θ is set based on the empirical analysis in Sect. 3.2. Our goal here is to study exclusively the quantitative implications of temperature volatility risk. We therefore abstract from studying the effects of temperature level shocks.

Market clearing Goods market clearing implies that

$$Y_t = C_t + I_t.$$

4.1 Calibration

We calibrate the proposed production economy at an annual frequency. A total of 18 parameters should be specified. More specifically, four for preferences, three relating to the final goods production technology and labor market, four describing the TFP process, and seven for temperature dynamics (see Table 2).

We first introduce and discuss more standard parameters. Most of these are in line with the recent macro-finance literature and set to be close to key business cycle and asset price

¹⁴ Note that differently from Donadelli et al. (2020) we do not model the impact of temperature level shock and thus impose $\tau_z = 0$.

Table 2 Benchmark calibration

Parameter	Description	EU	NA
Preferences			
β	Subjective time discount factor	0.988	0.988
ψ	Elasticity of intertemporal substitution	2	2
γ	Relative risk aversion	10	10
ν	Consumption share in utility bundle	0.3407	0.3407
Production and investment parameters			
α	Capital share in final good production	0.345	0.345
δ_K	Depreciation rate of physical capital	0.06	0.06
τ	Capital adjustment costs elasticity	0.7	0.7
TFP			
μ_a	Long-run mean of TFP	0.009	0.0005
σ_a	Volatility of short-run shocks to TFP	0.025	0.0205
ρ_x	Long-run TFP shock persistence	0.97	0.97
σ_x	Volatility of long-run shocks to TFP	$0.1*\sigma_a$	$0.1*\sigma_a$
Temperature			
μ_z	Long-run mean of average regional temperature	9.325°C	20.775°C
τ_θ	Impact of temperature volatility innovations on TFP growth	-0.0275	-0.02375
ρ_x^z	Long-run temperature-related TFP shock persistence	0.6	0.6
ρ_z	Temperature persistence parameter	0.4	0.4
ρ_θ	Persistence of volatility shocks to average regional temperature	0.75	0.75
σ_z	Standard deviation of level shocks to average regional temperature	0.305	0.475
σ_θ	Standard deviation of volatility shocks to average regional temperature	$0.25*\sigma_z$	$0.2755*\sigma_z$

This table reports the set of parameters used to calibrate (at an annual frequency) our production economies featuring long-run productivity and temperature risks

dynamics. To get an economy where the representative agent has preferences for early resolution of uncertainty, we set the coefficient of relative risk aversion, γ , and the elasticity of intertemporal substitution (IES), ψ , to values of 10 and 2, respectively. As in Bansal and Ochoa (2011), a value of 0.988 is used for subjective discount factor, β . The consumption share in the utility bundle \tilde{C} is chosen such that the steady-state supply of labor is around one third of the total time endowment of the household. Given the other parameters, this is achieved by setting $\nu = 0.3407$. In the production sector, the capital share α is equal to 0.345 as in Croce (2014). Regarding the adjustment cost parameters, τ is set to 0.7 as in Kung and Schmid (2015). The constants α_1 and α_2 are chosen such that there are no adjustment costs in the deterministic steady state. The depreciation rate of capital δ_K is set to 0.06 as in Croce (2014). The parameter μ_a for average annual TFP growth is set to values of 0.009 for Europe and 0.0005 for North America, as indicated by empirical data.¹⁵ The volatility of the short-run shock, σ_a , is calibrated to match the annual volatility of output growth observed in the macroeconomic data. We then calibrate the parameters

¹⁵ Note that throughout the paper, average regional macroeconomic and temperature variables are both computed using the simple average.

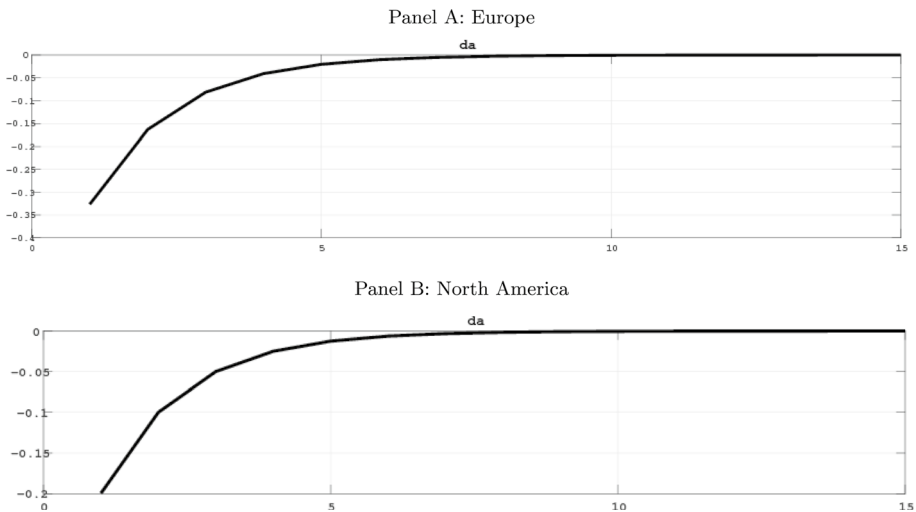


Fig. 5 Response of productivity to a temperature volatility shock. *Notes:* This figure depicts the impulse response of productivity growth to a temperature volatility shock in the regions Europe (Panel A) and North America (Panel B). Responses are expressed as percentage annual log-deviations from the steady state for a length of 15 years. All the parameters are calibrated to the values reported in Table 2

of the long-run productivity risk process, x_t , according to empirical estimates, resulting in $\rho_x = 0.97$ and $\sigma_x = 0.1\sigma_a$.

Let us now discuss the temperature-related parameters. The parameters measuring the sensitivity of TFP growth to temperature volatility shocks in the regions Europe (EU) and North America (NA) are jointly calibrated using the empirical evidence provided in Sect. 3.2. Therefore, the parameter τ_θ , measuring the impact of temperature volatility shocks on TFP growth, is calibrated to a value of -0.0275 for EU and to a value of -0.02375 for NA. This implies that model responses (see Fig. 5) are in line with empirical estimates (see Fig. 3). The persistence of the innovations in the long-run temperature risk component, ρ_z^x , is set to a value of 0.6 as in Donadelli et al. (2020).¹⁶ Regarding the stochastic volatility parameters in the temperature process, we set the persistence of temperature volatility shocks equal to 0.75, as suggested by empirical estimates. The standard deviation of time-varying temperature uncertainty, σ_θ , is assumed to be a small fraction of the volatility of temperature level shocks. Precisely, we impose $0.25 \cdot \sigma_z$ for EU and $0.2755 \cdot \sigma_z$ for NA. The other parameters regarding temperature dynamics are set to match the average regional temperature statistics observed in the data over the period 1991-2016. In particular, we set $\mu_z = 9.325$ (degrees Celsius) for EU and $\mu_z = 20.775$ for NA, $\rho_z = 0.4$, and $\sigma_z = 0.305$ for EU and $\sigma_z = 0.475$ for NA to match the long-term mean, persistence and volatility of region-specific average temperature, respectively.

Given these parameters, we use perturbation methods to solve our system of equations. We compute an approximation of the third order of our policy functions using the `dynare++ 4.4.3` package.

¹⁶ Note that one can interpret the parameter ρ_z^x as the speed of adaptation (see e.g. Tol 2002). A value of 0 refers to the case of an immediate adaptation to temperature-related shocks while a value of 1 would imply no adaptation.

Table 3 Simulated moments

	Model (EU)	Model (NA)	Data (EU)	Data (NA)
<i>Macro</i>				
$\mathbb{E}(\Delta a)$	0.9	0.1	0.9	0.0
$\sigma(\Delta y)$	2.6	2.0	2.6	2.0
$\sigma(\Delta c)$	2.1	1.7	2.3	2.3
$\sigma(\Delta i)/\sigma(\Delta y)$	1.8	1.9	4.4	3.1
<i>Temperature</i>				
$\mathbb{E}(T)$	9.3	20.8	9.3	20.8
$\sigma(T)$	0.5	0.3	0.5	0.3
<i>Asset Prices</i>				
$\mathbb{E}[Rm - Rf]$	3.7	2.1	6.9	9.1
$\mathbb{E}[Rf]$	0.2	0.5	2.0	0.9
$\sigma(Rm - Rf)$	5.4	4.3	20.3	17.8
$\sigma(Rf)$	0.8	0.6	2.2	2.2

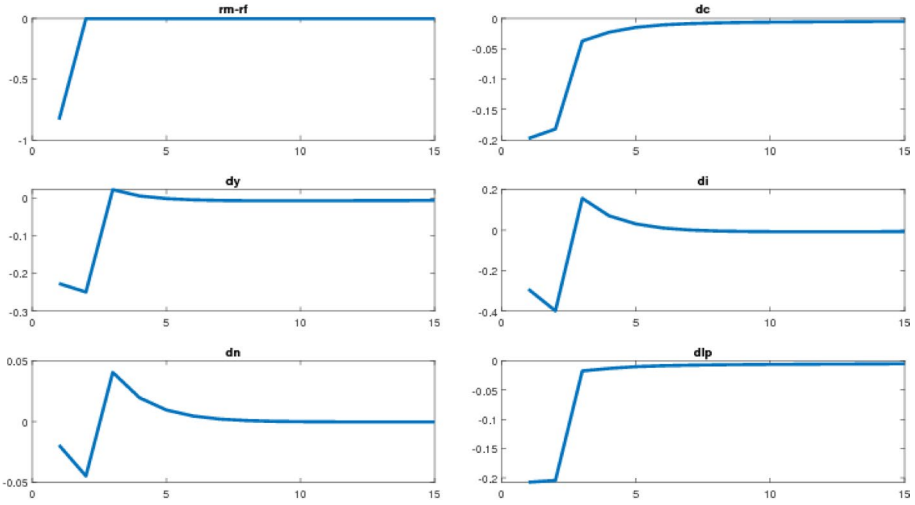
This table reports the main moments for the calibrations for Europe (EU) and North America (NA). The levered equity risk premium is defined as $R_{ex}^{LEV} = (1 + \frac{D}{E})(R_t - R_{t-1}^f)$ where financial leverage is imposed by assuming an average debt-to-equity ratio $\frac{D}{E}$ of 1 (see, e.g., Croce 2014; Hitzemann et al. 2016). Models' entries are obtained from repetitions of small-sample simulations (i.e., averages over 1000 simulations of 100 years). $\mathbb{E}[\cdot]$ and $\sigma(\cdot)$ denote mean and volatility, respectively. Mean and volatility values are expressed in percentage points. Empirical moments are computed from annual regional average data across countries, spanning the period 1991–2016

4.2 Quantitative Results

Macro-quantities and asset prices, and IRFs The main results are reported in Table 3. The model matches well macroeconomic quantities and temperature dynamics. In line with standard long-run risk models, our framework produces relatively high values of average excess returns and relatively low risk-free rates as suggested by international capital markets data. However, the relatively low output volatility does not allow the model to fully account for the 6.9% and 9.1% equity risk premium observed in Europe and North America, respectively.

To analyze how temperature volatility shocks are transmitted through the economy, we plot the responses of macro quantities to an unexpected increase in temperature volatility (see Fig. 6). This shock negatively affects the temperature-related long-run risk component of productivity growth. While long-run macro shocks have a delayed effect on productivity, an unexpected temperature volatility increase reduces productivity growth on impact, as found in our empirical analysis. This translates into an immediate decrease in consumption growth and a decrease in investment, which reduces total output growth. As unexpected increases in temperature-volatility reduce productivity, firms' profits decline leading to a negative effect on dividends. Due to the fall in investment, the price of capital depreciates, which implies lower stock market returns and a contemporaneous increase in the stochastic discount factor. As equity markets experience a contraction, the agent's demand for risk-less securities increases, producing a drop in the risk-free rate. As the returns on the aggregate stock market decrease more

Panel A: Europe



Panel B: North America

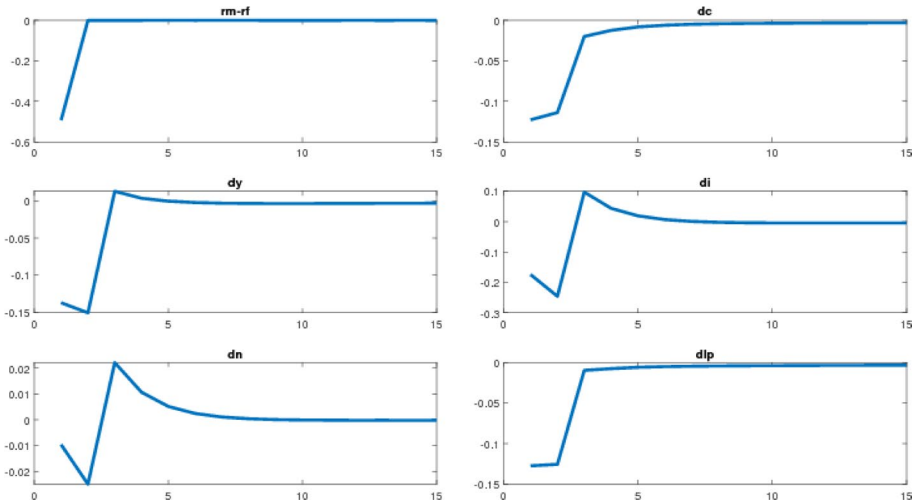


Fig. 6 Response of productivity to a temperature volatility shock. *Notes:* This figure depicts the impulse response of market excess return, $rm - rf$, consumption growth, dc , output growth, dy , investment growth, di , labor growth, dn and labor productivity growth, dlp to a temperature volatility shock in the regions Europe (Panel A) and North America (Panel B). Responses are expressed as percentage annual log-deviations from the steady state for a length of 15 years. All the parameters are calibrated to the values reported in Table 2

than the risk-free rate, the excess return declines as well as depicted in Fig. 6. This also means that the equity market does not provide insurance against temperature volatility risk. There is no positive excess return when the marginal utility of the agent is high, i.e. in a bad state of the world. In this respect, temperature volatility risk is associated with higher equity risk premia.

Table 4 Temperature volatility-
implied welfare costs: Europe
versus North America

	Europe ($\tau_\theta = -0.0275$)	North America ($\tau_\theta = -0.02375$)
Welfare costs (benchmark calibration)	2.9	1.0

This table reports the welfare costs of temperature volatility ($\sigma(T)$) shocks for the regions Europe and North America. Welfare costs are defined as the percentage increase $\Delta > 0$ in composite consumption (\tilde{C}) that the household should receive in every state and at every point in time in order to be indifferent between living in an economy with full risk exposure (i.e., $\sigma_z, \sigma_a, \sigma_x, \sigma_\theta > 0$) and an economy with no temperature volatility risk. Temperature volatility risk is eliminated by imposing $\tau_\theta = 0$

Welfare costs In the spirit of Bansal and Ochoa (2011), we measure the economic costs of temperature volatility risk by means of welfare compensation of a change in the level of temperature volatility. The welfare compensation is expressed as a permanent change of agent's lifetime utility relative to the economy with no temperature volatility risk. Formally,

$$\mathbb{E}[U_0((1 + \Delta)\tilde{C})] = \mathbb{E}[U_0(\tilde{C}^*)], \quad (5)$$

where Δ represents welfare-costs, and $\tilde{C} = \{\tilde{C}_t\}_{t=0}^\infty$ and $\tilde{C}^* = \{\tilde{C}_t^*\}_{t=0}^\infty$ denote the optimal consumption paths with and without temperature volatility risk, respectively.

Table 4 reports welfare costs for temperature volatility effects in EU and NA. In these regions welfare costs amount to 2.9% and 1.0% of per capita composite consumption, respectively. This means that for EU (NA), the bundle consisting of consumption and leisure of an agent living in an economy with temperature volatility risk needs to be increased by 2.9% (1.0%) in every state and at every point in time to give the agent the same utility as in an economy without temperature volatility risk. Since temperature volatility shocks have a large and persistent effect on productivity as well as on other macroeconomic and financial variables, they produce significant welfare costs.

5 Concluding Remarks

This paper examines the historical relationship between temperature volatility and productivity growth. We find novel empirical evidence indicating that increasing uncertainty on temperature variability (i.e., temperature volatility) has significant implications for productivity growth in different macro-regions around the globe. However, effects differ across regions. While, over the period 1955-2016, productivity growth in Europe and North America is negatively affected by an unexpected increase in intra-annual temperature volatility, a positive relationship between intra-annual temperature volatility and productivity growth is found for Asia. Moreover, the sign of the relationship between productivity and temperature volatility can be different across regions when considering a different proxy for temperature volatility, i.e., inter-annual temperature volatility. Naturally, intra-annual and inter-annual temperature volatility capture different aspects of temperature variability

and more research needs to be done on the transmission channels through which changes in temperature variability affect macroeconomic activity. To quantify our empirical findings on negative temperature volatility effects in Europe and North America, we use a standard production economy featuring long-run macro and temperature volatility risk. In the model, temperature volatility shocks (1) dampen productivity growth, the growth rate of key macro-aggregates, and equity valuations and (2) generate non-negligible welfare costs.

Taken together, our novel evidence on the implications of rising variability in temperature levels indicates that climate change seems to have stronger economic effects among advanced economies. Therefore, the design and implementation of green policies aimed at reducing the adverse effects of climate change variability should be at the center of the policy agenda of major industrialized countries. In particular, based on our evidence, it is most likely that short-run policies would result more effective than long-run ones in reducing the adverse effects of intra-annual and inter-annual temperature variations.

Appendix: Additional Empirical Results

1. Intra-Annual Temperature Volatility: Descriptives

See Figs. 7 and 8.

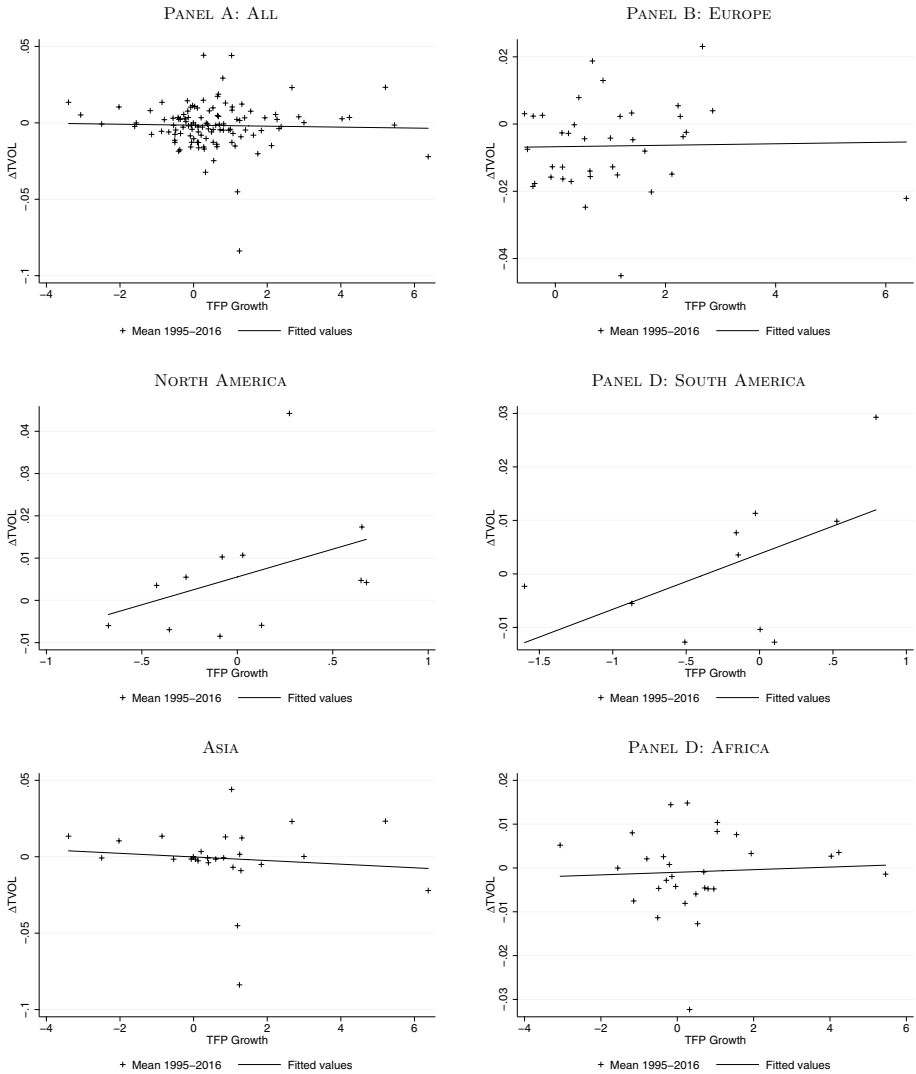


Fig. 7 Changes in temperature volatility versus productivity growth (by Region). *Notes:* This figure plots for each country the 1995–2016 average of annual first differences in intra-annual temperature volatility against the 1995–2016 average in annual TFP growth. Solid black line: estimated regression line

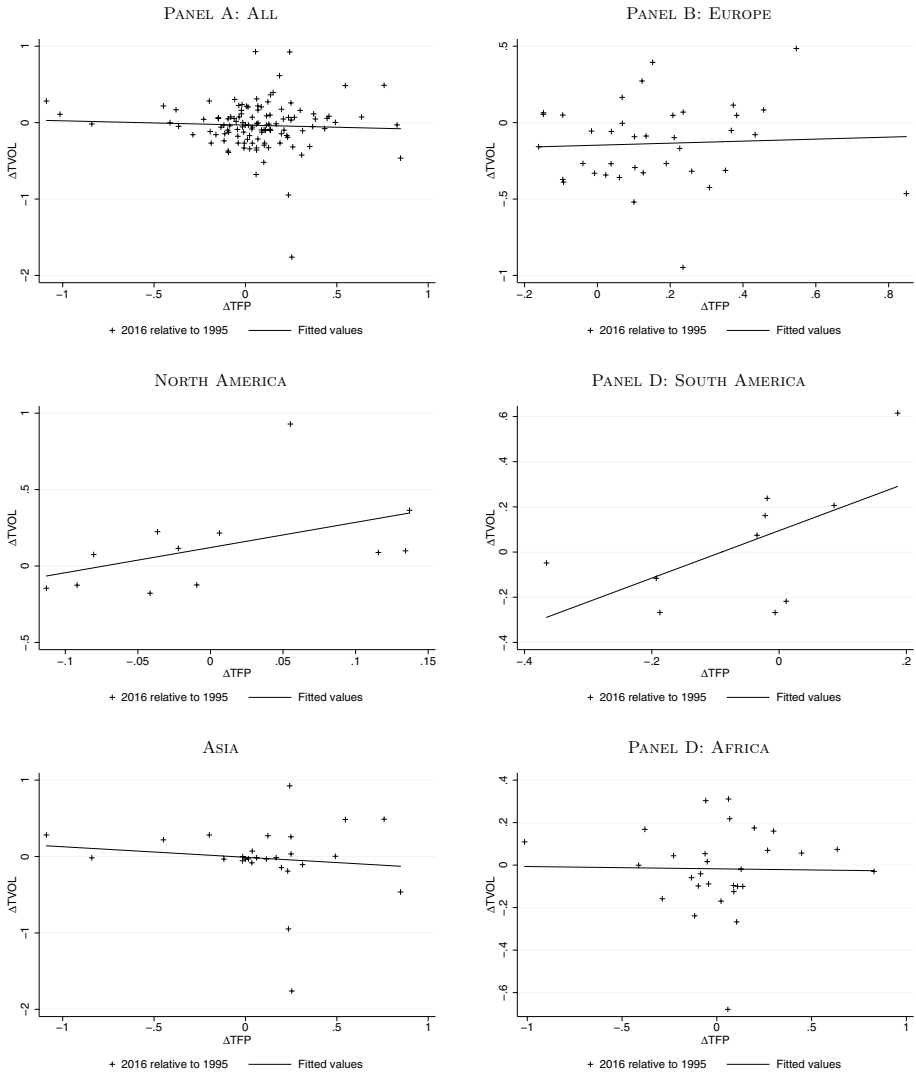


Fig. 8 Long run changes in temperature volatility versus long-run changes in TFP (by Region). *Notes:* This figure plots for each country the change in intra-annual temperature volatility between 1995 and 2016 against the change in TFP between 1995 and 2016. Solid black line: estimated regression line

2. Intra-Annual Temperature Volatility: Simple Impulse Responses

See Fig. 9.

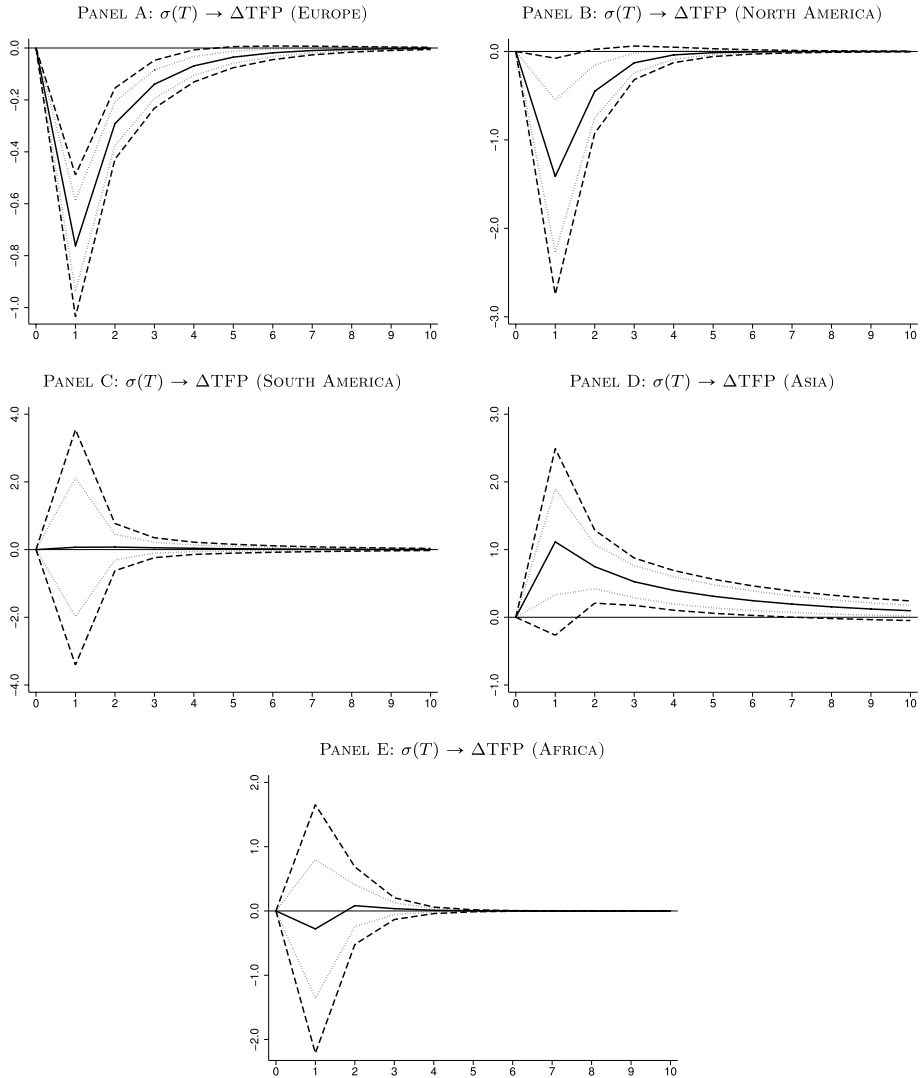


Fig. 9 Impulse Response of TFP Growth to a temp-vol shock in different regions. *Notes:* This figure presents simple (non-orthogonalized) impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

3. Intra-Annual Temperature Volatility: Controlling for Capital

See Fig. 10.

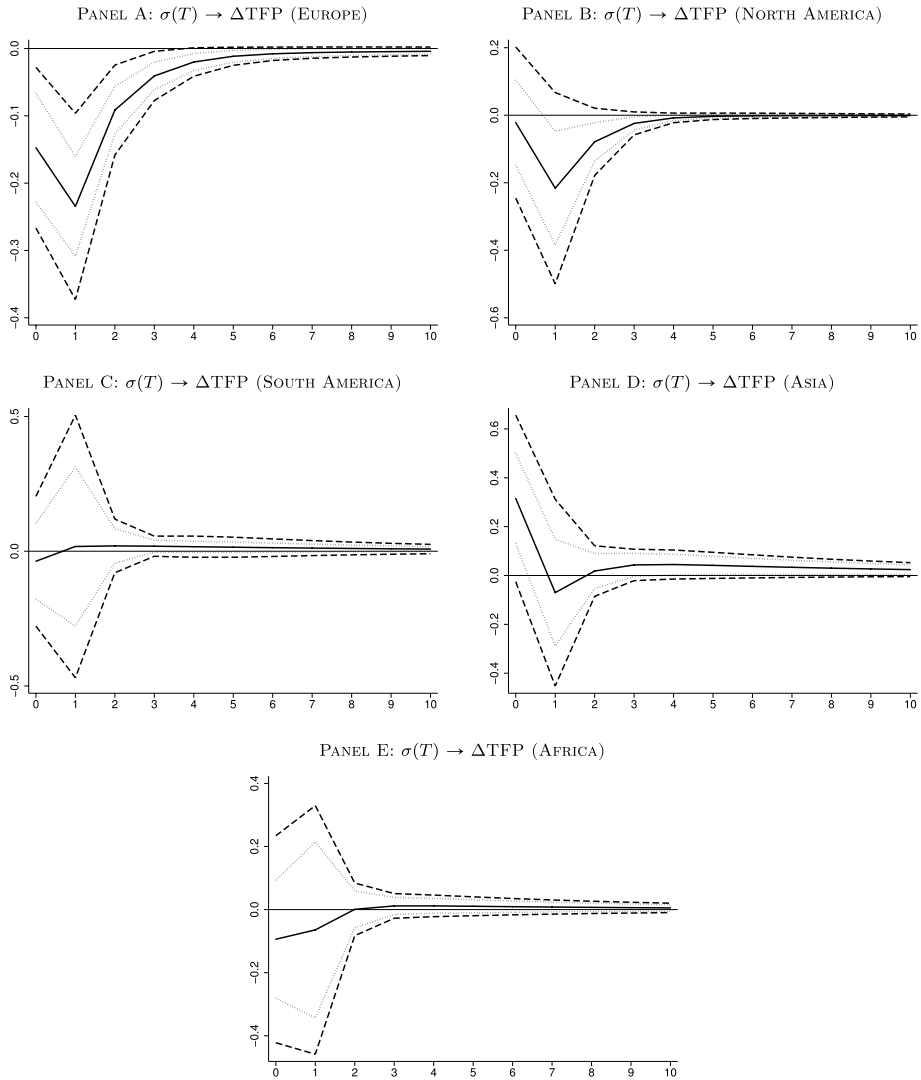


Fig. 10 Impulse Response of TFP Growth to a temp-vol shock in different regions. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, capital growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

4. Inter-Annual Temperature Volatility

See Figs. 11, 12.

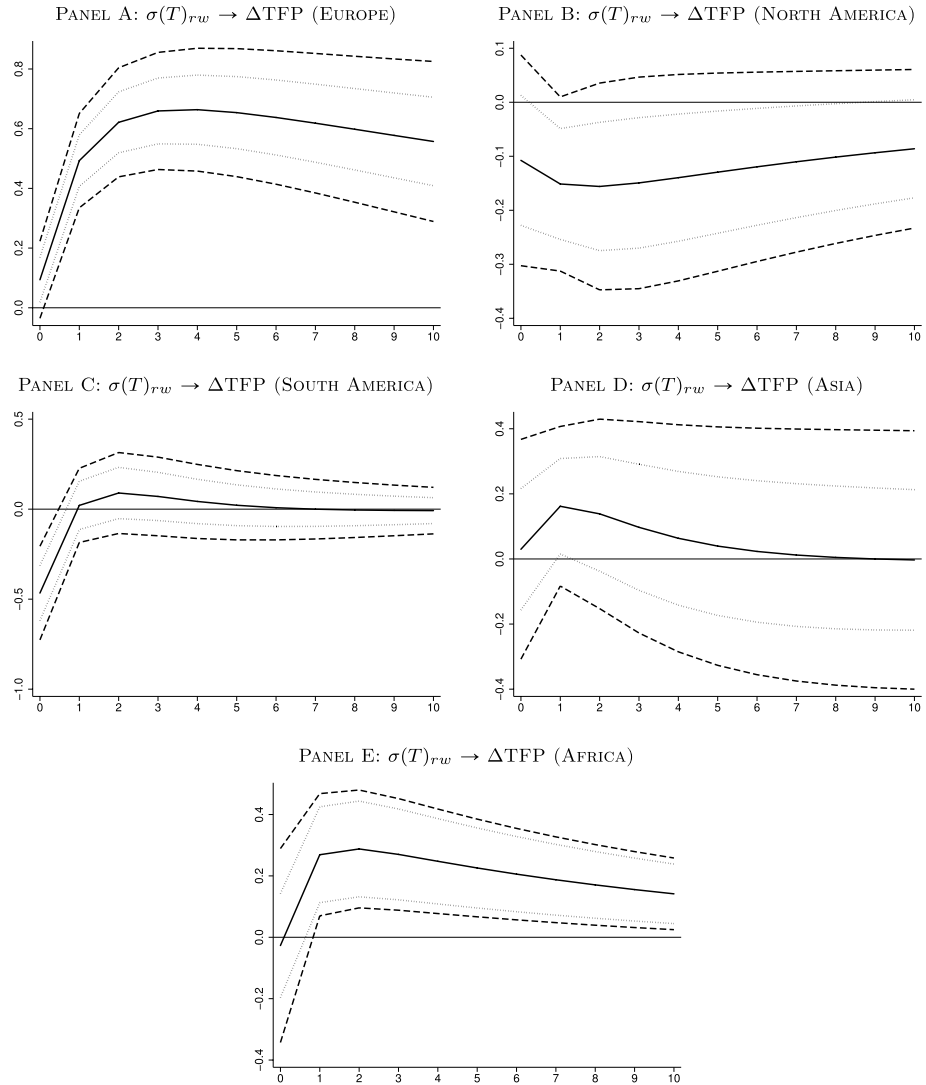


Fig. 11 Impulse Response of TFP Growth to an inter-annual temperature volatility shock. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an inter-annual temperature volatility shock [$\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

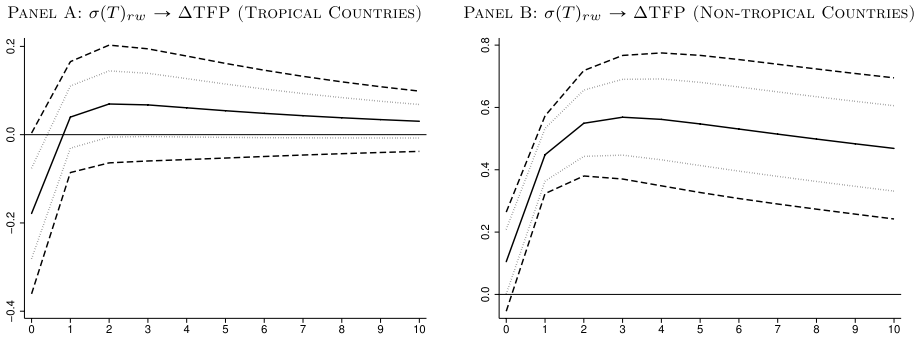


Fig. 12 Impulse Response of TFP Growth to an inter-annual temperature volatility shock: tropical versus non-tropical countries. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an inter-annual temperature volatility shock [$\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

5. Panel VAR: Post-1975 Results

5.1. Intra-Annual Temperature Volatility

See Figs. 13, 14.

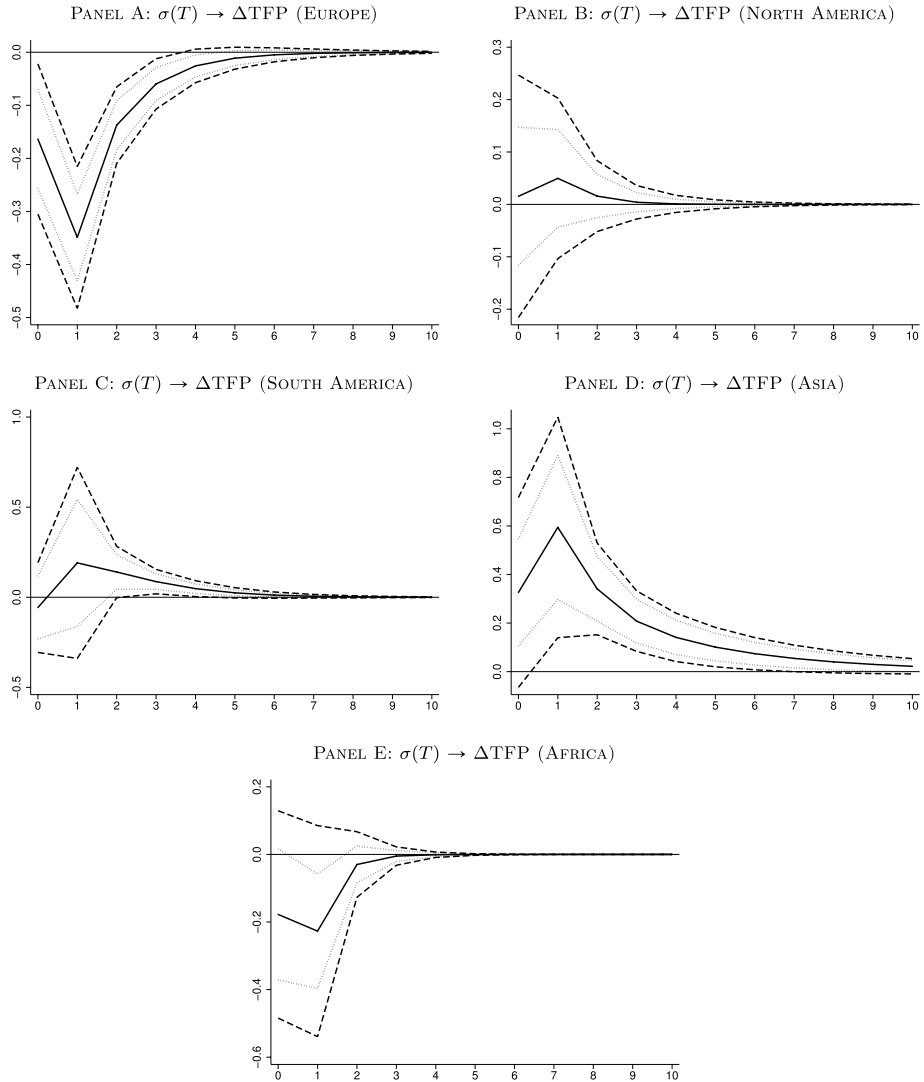


Fig. 13 Impulse Response of TFP Growth to an intra-annual temp-vol shock in different regions (1975-2016). *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1975 to 2016

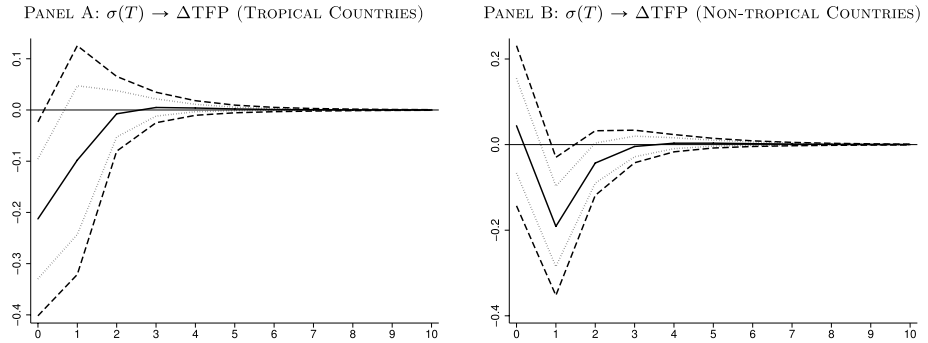


Fig. 14 Impulse Response of TFP Growth to an intra-annual temp-vol shock: tropical versus nontropical countries. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1975 to 2016

5.2. Inter-Annual Temperature Volatility

See Figs. 15, 16.

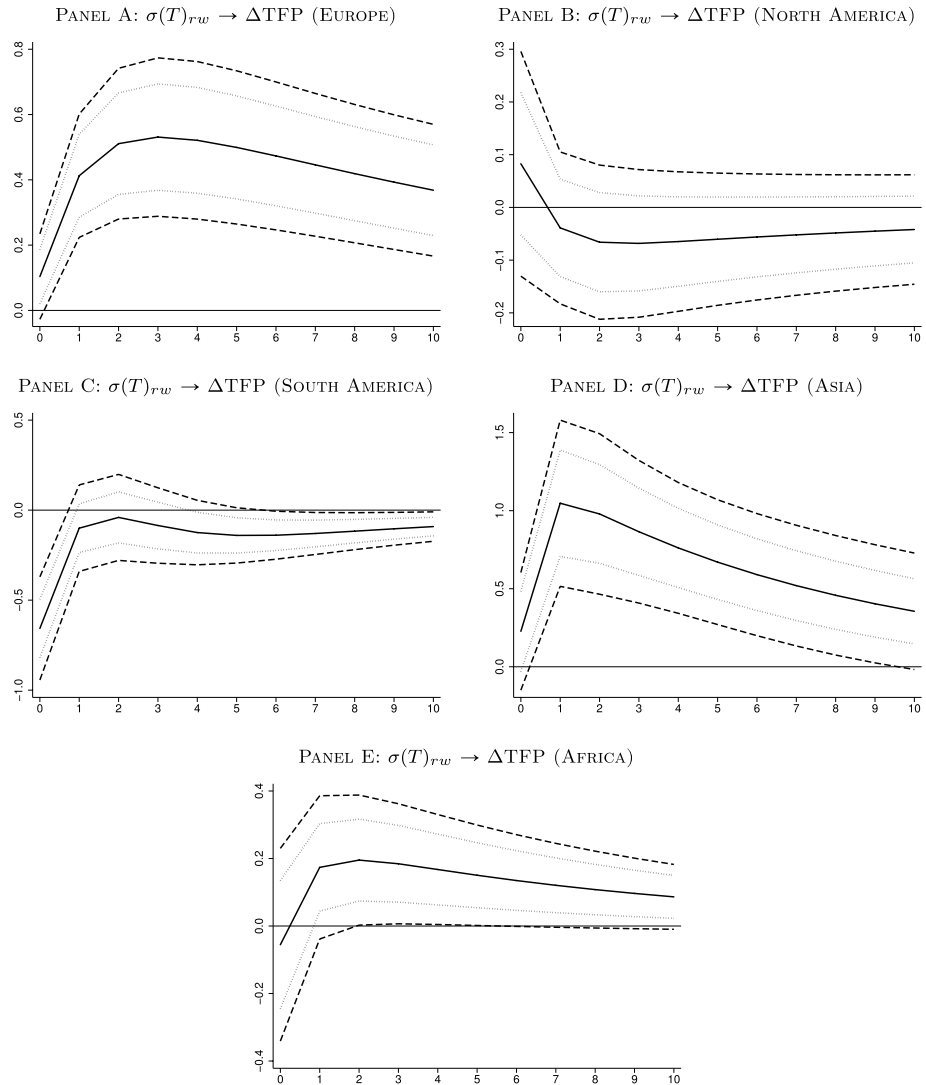


Fig. 15 Impulse Response of TFP Growth to an inter-annual temp-vol shock in different regions (1975–2016). *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an inter-annual temperature volatility shock [$\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: inter-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1975 to 2016

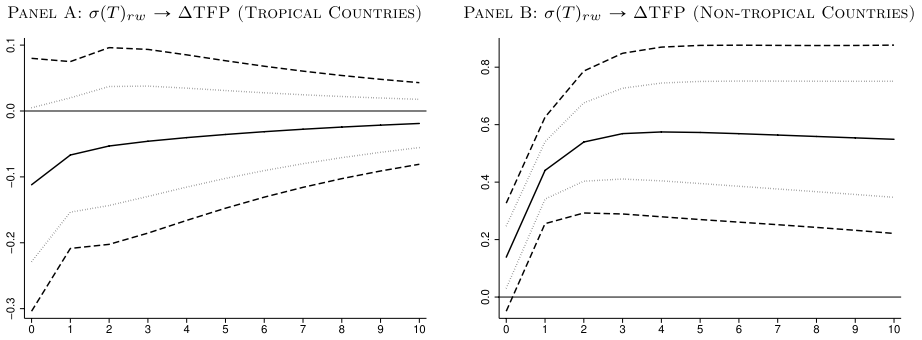


Fig. 16 Impulse Response of TFP Growth to an inter-annual temp-vol shock: tropical versus non-tropical countries. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an inter-annual temperature volatility shock [$\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: inter-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1975 to 2016

6. Intra-Annual Temperature Volatility: Different Sub-Regions

See Fig. 17.

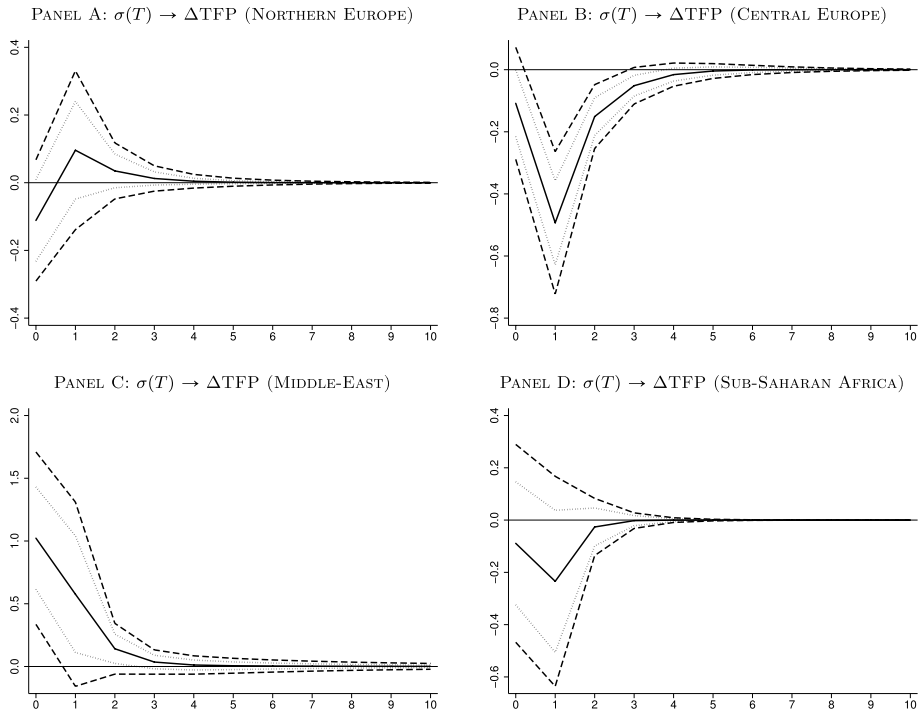


Fig. 17 Impulse Response of TFP Growth to a temp-vol shock in different regions. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to an intra-annual temperature volatility shock [$\sigma(T)$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: intra-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

7. Inter-Annual Temperature Volatility: Winter

See Fig. 18.

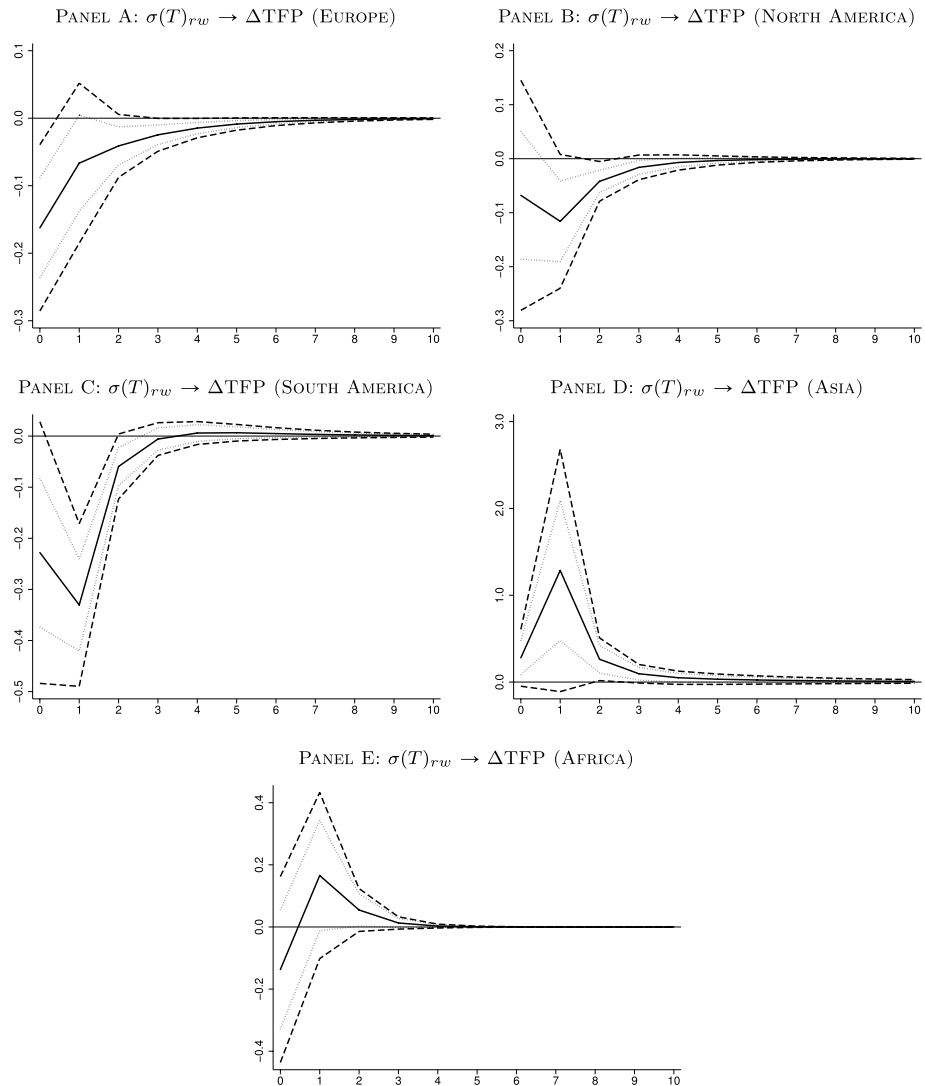


Fig. 18 Impulse Response of TFP Growth to an inter-annual winter temperature volatility shock. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to a shock in the first-difference of inter-annual winter temperature volatility (Jan, Feb, Mar) [$\Delta\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: inter-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

8. Inter-Annual Temperature Volatility: Spring

See Fig. 19.

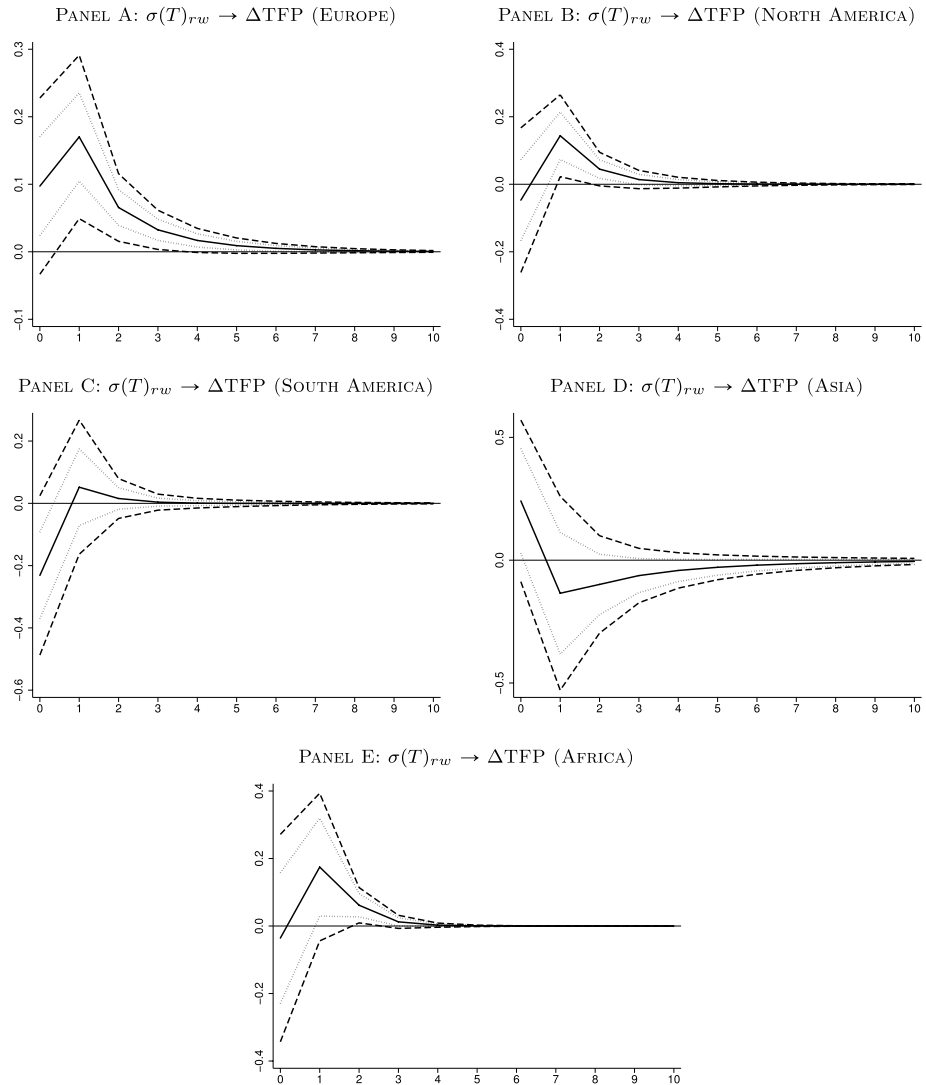


Fig. 19 Impulse Response of TFP Growth to an inter-annual spring temperature volatility shock. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to a shock in the first-difference of inter-annual spring temperature volatility (Apr, Mai, Jun) [$\Delta\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: inter-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

9. Inter-Annual Temperature Volatility: Summer

See Fig. 20.

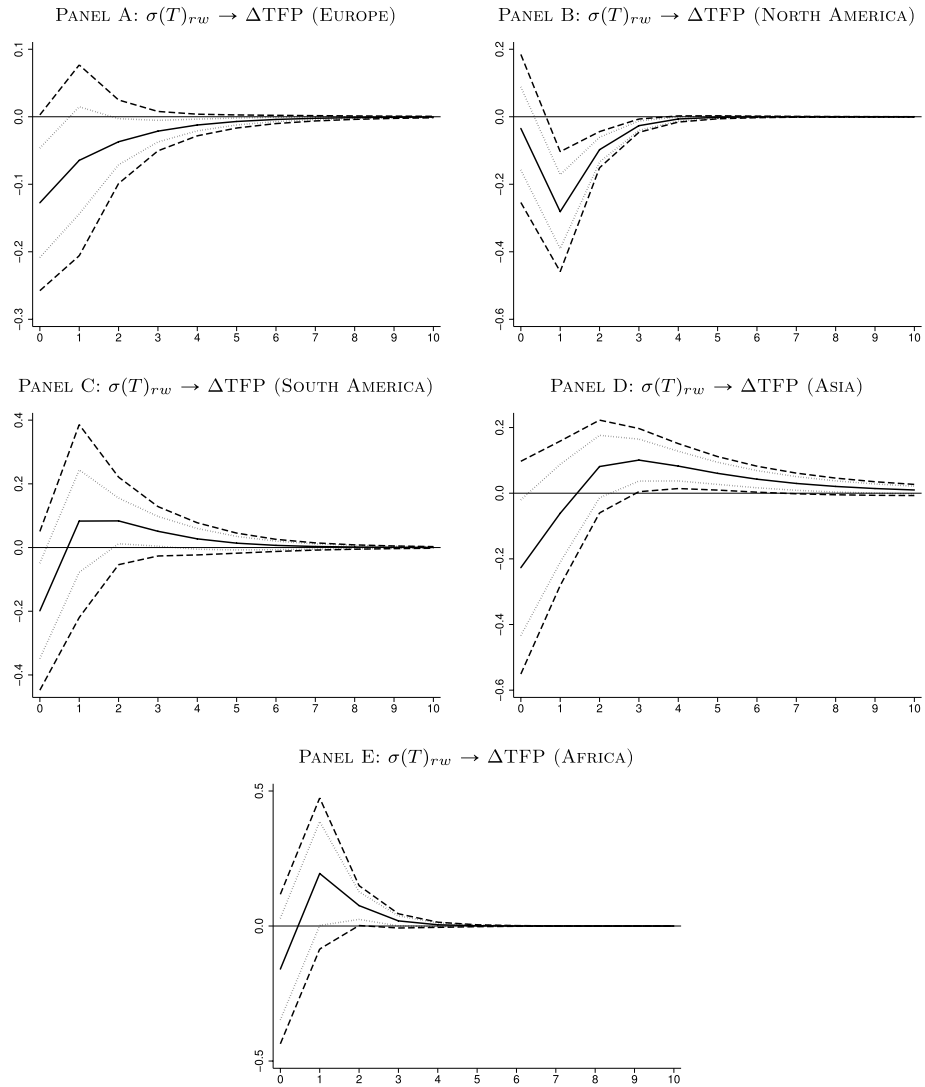


Fig. 20 Impulse Response of TFP Growth to an inter-annual summer temperature volatility shock. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to a shock in the first-difference of inter-annual summer temperature volatility (Jul, Aug, Sep) [$\Delta\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: inter-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

10. Inter-Annual Temperature Volatility: Fall

See Fig. 21.

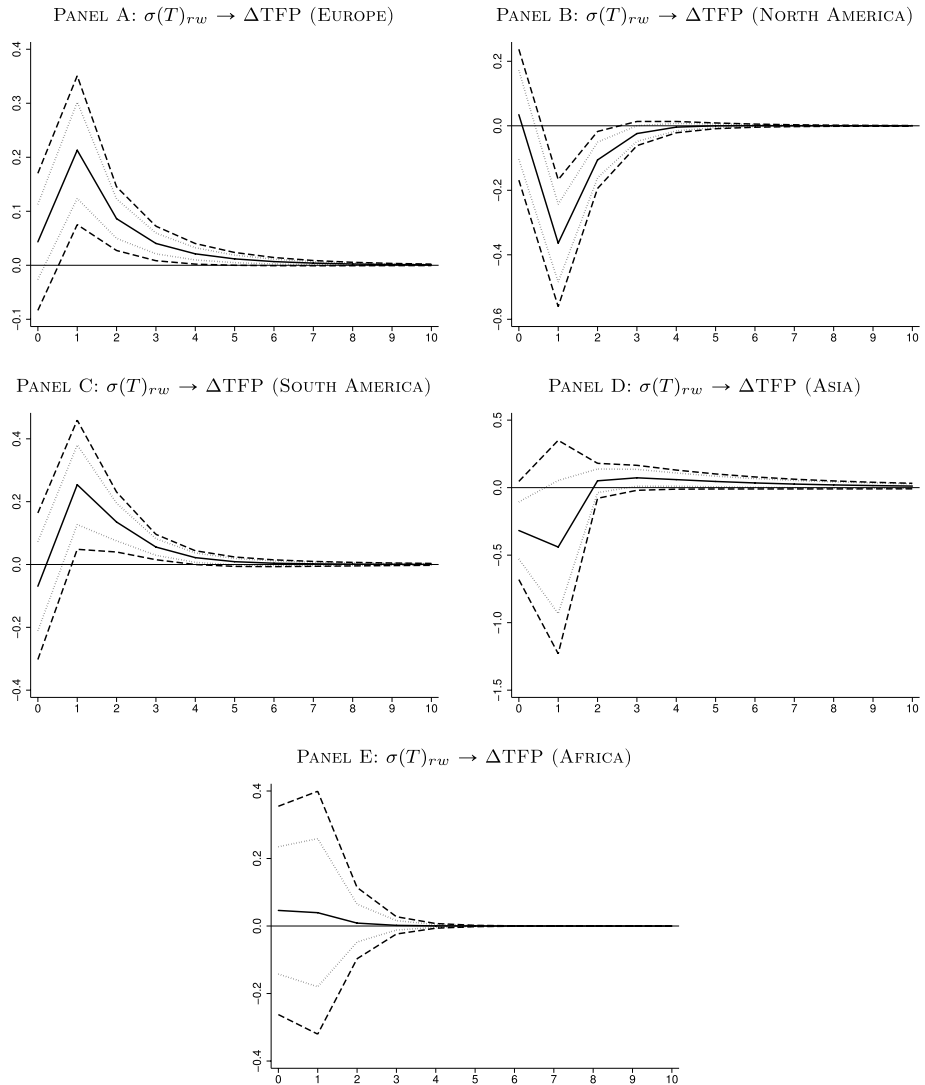


Fig. 21 Impulse Response of TFP Growth to an inter-annual fall temperature volatility shock. *Notes:* This figure presents Cholesky orthogonalized impulse responses of TFP growth to a shock in the first-difference of inter-annual fall temperature volatility (Oct, Nov, Dec) [$\Delta\sigma(T)_{rw}$]. Impulse responses are obtained by estimating a panel VAR(1) (Eq. 1) using the Generalized Method of Moments (GMM). We order the variables in vector Y as follows: inter-annual temperature volatility, GDP growth, TFP growth (i.e., temperature volatility is the most exogenous variable). The lag order of the dependent variables to be used as instruments is chosen to be four. The panel VAR satisfies the stability conditions. Solid black lines: estimated impulse responses. Dashed lines: 90% bootstrapped confidence bands. Dotted lines: 68% bootstrapped confidence bands. Robust standard errors are computed by clustering standard errors at the country level. Data are annual and span the period from 1955 to 2016

11. Intra-Annual Temperature Volatility: Standard Panel Results

To analyze the effects of intra-annual temperature volatility on TFP growth, we estimate the following equation:

$$\Delta TFP_{i,t} = c_i + \beta\sigma(T)_{i,t} + \gamma\Delta GDP_{i,t} + v_t + \varepsilon_{i,t}, \quad (6)$$

where $\Delta TFP_{i,t}$ is the TFP growth rate of country i in year t and $\Delta GDP_{i,t}$ is the GDP growth rate of country i in year t . The estimation includes country and year fixed effects. Standard errors are clustered at the country level. Estimating Eq. A.1 by region, negative temperature volatility effects are significant at the 10% level for North America. For Europe, the temperature volatility coefficient is very close to being significant at the 10 % level. For South America, the temperature volatility coefficient is also negative but insignificant, whereas it is positive but insignificant for Asia and Africa. We also estimate the equation using all countries [specification (6)], adding a term where temperature volatility is interacted with a poor country dummy ($\sigma(T)\times Poor$). As in Dell et al. (2012), *Poor* is defined as a dummy for a country having below median PPP GDP per capita in its first year in the data. Results show that temperature volatility effects are not significantly different for poor countries compared to rich countries. See Table 5.

Table 5 Effects of temperature volatility on TFP growth (by Region)

	(1) Europe	(2) North America	(3) South America	(4) Asia	(5) Africa	(6) All regions
$\sigma(T)$	-0.213 (0.127)	-0.475 * (0.220)	-0.743 (0.461)	0.070 (0.482)	0.198 (0.902)	-0.015 (0.150)
ΔGDP	0.690*** (0.030)	0.729*** (0.031)	0.776*** (0.017)	0.848*** (0.044)	0.863*** (0.036)	0.818*** (0.028)
$\sigma(T)\times Poor$						-0.302 (0.409)
N	1761	672	603	1283	1334	5623
Sample	1955-2016					

Standard errors in parentheses

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

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