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GLOBAL TEMPERATURE, R&D EXPENDITURE, AND GROWTH[*]

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Abstract

We shed new light on the macroeconomic effects of rising temperatures. In the data, a shock to global temperature dampens research and development (R&D) expenditure growth. This novel empirical evidence is rationalised within a stochastic endogenous growth model. In the model, Temperature shocks undermine economic growth via a drop in R&D. Moreover, temperature risk generates welfare costs of 13.50% of lifetime utility. The government can offset these welfare costs by subsidizing investment with 1.02% or R&D expenditure with 0.52% of total public spending, respectively. Alternatively, it can levy a lump-sum tax on households which finances 0.64% of total public spending.

Keywords: Global temperature, Endogenous growth, R&D expenditure, Welfare costs

JEL: E30, G12, Q00

1 Introduction

Rising global temperature has spawned an intense academic and international policy debate and has placed into question the sustainability of the global economy. Whilst economists and policy makers generally agree that climate change can generate huge costs for the economy and society, there is no consensus on i) the mechanism through which such costs originate, ii) the industries which are likely to be most affected by rising temperatures, and iii) the scale of such costs. Concerning the mechanism of climate change effects, in a speech on the global warming-financial stability nexus at Lloyd's of London, the governor of the Bank of England, Mark Carney, underscored three broad channels: physical risks, liability risks, and transition risks.[1] The latter refers to financial risks resulting from the process of adjustment towards a lower-carbon economy and triggering a revaluation of assets.

Against this background, our research aims to i) evaluate the empirical effects of temperature shocks on R&D expenditure growth, ii) shed light on the theoretical mechanism that translates rising global temperature into lower R&D spending, depressed income growth, and a deterioration of welfare, and iii) design government policies that seek to offset the welfare costs provoked by rising global temperature. Our research contributes to the related literature in three remarkable ways. First, we provide novel empirical evidence on the effects of temperature shocks on the macroeconomy. We extend previous empirical studies (e.g., Colacito, Hoffmann, and Phan, 2016) by investigating the effects of temperature increases on R&D expenditure growth, a channel that has not thus far been investigated. Using data for a sample of countries that encompasses the G7 and the OECD, we find that a rise in global temperature undermines growth in R&D expenditure in a significant and persistent way. Second, given our empirical results, it is straightforward to model climate risk in a framework where technical progress is endogenous. More specifically, we introduce temperature dynamics, as modeled in Bansal and Ochoa (2011b), into a stochastic endogenous growth model in the spirit of Kung and Schmid (2015) where temperature shocks negatively affect the accumulation of patents and, consequently, R&D expenditure growth. Using the calibrated model, we find that temperature risk produces sizable welfare costs of 13.50% of lifetime consumption. These welfare costs can be offset by subsidizing capital investment with around 1.02% of total government expenditure.[2]

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[1] http://www.bankofengland.co.uk/publications/Pages/speeches/2015/844.aspx.

[2] Similarly, the need for investment in physical capital is also emphasised in Angelopoulos, Economides, and Philippopoulos (2013), who find that environmental uncertainty leads to an increase in investment

Alternatively, the government can either use 0.52% of total government expenditure to finance a R&D expenditure subsidy or levy a lump-sum tax on households that finances roughly 0.64% of total government expenditure to completely offset the welfare costs of temperature risk. Global temperature shocks reduce long-run growth perspectives in our model as they are assumed to harm the accumulation of patents by increasing their obsolescence rate, which, consequently, decreases long-run productivity. Third, our research may contribute to environmental, fiscal, and social policy debate and advice. Specifically, our research findings indicate that environmental degradation makes R&D patents obsolete at an increasing rate, which translates into a significant welfare burden in the long run. One way to prevent or reduce such a burden would be to incorporate the stylised temperature change, output, and welfare nexus into the government's objective function.

The remainder of this paper is structured as follows. In Section 2, we review the related literature. Section 3 documents the novel empirical evidence regarding the effects temperature shocks on R&D that survives a battery of robustness checks. In Section 4, we develop the dynamic stochastic endogenous growth general equilibrium model. Sections 5 and 6 present our benchmark calibration and the quantitative results, respectively. Five important quantitative robustness checks are relegated to Section 7. Finally, Section 8 provides concluding remarks.

2 Related Literature

Empirically, our paper fits into a growing literature that explores the implications of rising temperatures for real economic activity. Bansal and Ochoa (2011b), for instance, find that a global temperature shock (i.e. a rise in temperature of 0.2°C) reduces world consumption growth by 0.2 percentage points (pp). They also observe that this effect lasts for several years. Dell, Jones, and Olken (2012) report that higher temperatures substantially reduce economic growth in poor countries, while Deryugina and Hsiang (2014) demonstrate that an increase in daily average temperature above 15°C is associated with a substantial reduction in U.S. personal income. Still focusing on the U.S., Colacito, Hoffmann, and Phan (2016) show that a 1°F increase in average summer temperature produces a reduction in output growth of (around) 0.2pp. Du, Zhao, and Huang (2017) observe that a rise in long-run temperature undermines output growth

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through precautionary behaviour, ultimately leading to an improvement in welfare.

not only in the U.S. but also in the euro area. We extend these studies by examining the effects of rising temperatures on R&D expenditure.

From a quantitative point of view, our research seeks to shed light on the theoretical channels of the stylised negative income effect of temperature increases. In this respect, we are connected to the strand of literature that integrates environmental economics with macroeconomics and focuses on the effects of environmental degradation on the economy. Prominent in this strand are studies that embed environmental policy and temperature dynamics in real business cycle (RBC) models. Fischer and Springborn (2011) and Heutel (2012), for instance, investigate how optimal climate policies should be designed under stochastic productivity shocks. Bansal and Ochoa (2011b), for their part, propose an augmented long-run risk model in which temperature negatively impacts long-run growth. Specifically, the model captures the long-lasting effect that global temperature has on world consumption growth observed in the data. Based on the empirical evidence that temperature shocks undermine total factor productivity growth, Donadelli, Jüppner, Riedel, and Schlag (2017), following the approach of Bansal and Ochoa (2011b), integrate U.S. temperature dynamics into a production-based model featuring recursive preferences, long-run productivity risk, and investment adjustment costs. We differ from these theoretical approaches which aim to study the macroeconomic effects of climate change-related phenomena in that we analyse the welfare implications of rising temperatures within a stochastic endogenous growth framework.[3] This is in line with our novel empirical evidence showing that rises in temperature level directly affect R&D expenditure growth (i.e. the most productive sector of the economy).

Another stream of literature concentrates on New Keynesian dynamic stochastic general equilibrium models that incorporate pollutant emissions and the design of environmental policy. One example is Annicchiarico and Di Dio (2015), in which the performance of alternative environmental policy rules under real and nominal uncertainty, as well as the interaction between environmental and monetary policy, are studied. In a similar vein, Annicchiarico and Di Dio (2017) investigate the optimal monetary and environmental policy mix. They show that optimal policy design depends on the intensity of distortions policy makers have to address, the

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[3] This means that our model incorporates temperature risk, a government, and endogenous growth with horizontal innovations, similarly to Romer (1990), into an otherwise fairly standard RBC model with a representative household and a representative final goods firm, i.e. all quantities are real and we abstract from typical New Keynesian elements such as price rigidities or monetary policy. In this respect, our model directly builds on the one proposed by Kung and Schmid (2015).

instruments they have available, and the way they interact. Differently from Annicchiarico and Di Dio (2015), who assume a closed economy, Ganelli and Tervala (2011) evaluate the degree to which environmental policy shocks can be transmitted internationally within a full-fledged open economy New Keynesian model. Furthermore, while in Annicchiarico and Di Dio (2015), the pollutant stock undermines productivity of firms, key to the model of Ganelli and Tervala (2011) is a productivity enhancing factor that includes both the quality of the environment and the flow of polluting emissions. Broadly speaking, we differ from this analysis in at least two main respects. First, we abstract from finding optimal policies. Second, like many other studies, we focus exclusively on global temperature dynamics as a proxy for climate change.

Most closely related to us are studies modelling climate effects in an endogenous growth setting. Using different standard models, Fankhauser and Tol (2005) analyse the effects of climate change on capital accumulation and saving. van der Zwaan, Gerlagh, Klaassen, and Schrattenholzer (2002) find that introducing endogenous technological change affects optimal climate policies and the path of emission reduction.[4] More recently, and in line with empirical evidence (e.g., Dell, Jones, and Olken, 2012), Dietz and Stern (2015) specify climate change to affect long-run growth. Moreover, they introduce climate risk and allow the damage of global warming to increase rapidly from some temperature level on to reflect catastrophic climate damages after a certain degree of global warming. In contrast to the standard literature on so-called integrated assessment models (e.g., Nordhaus, 2008), Dietz and Stern (2015) require strong emission cuts. Our modelling approach is novel in the sense that we take into account all the elements mentioned above, i.e. climate risk, stochastic productivity, and long-run growth effects of temperature increases.

3 Empirical Analysis

Recent studies document that rising temperatures may have sizable adverse effects on economic activity. Using a novel dataset on private and public R&D expenditure provided by the OECD Main Science and Technology Indicators, we shed new light on the macroeconomic effects of rising temperatures. Specifically, by means of standard empirical methodologies, we study the impact of global temperature shocks on aggregate R&D expenditure growth. The main results of

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[4] A literature review on climate policy analysis under endogenous technological progress is provided by Gillingham, Newell, and Pizer (2008).

this analysis are reported in Figure 1, Table 1, and Figure 2 and discussed in Section 3.1. Results from a battery of robustness tests are discussed in Section 3.2. For the purpose of illustration, the global temperature series for the period 1981–2014 is depicted in Figure A.1 in Appendix A. Section 3.3 briefly summarises the main take-away from our empirical analysis.

3.1 Temperature Shocks and R&D

Bivariate VAR analysis. In the spirit of Bansal and Ochoa (2011b), we first estimate a bivariate VAR model of G7 Business Enterprise Expenditure in R&D (BERD) growth and global temperature.[5] Global temperature is ordered first, and thus the VAR(1) model is given by:

$$Z_t = C + AZ_{t-1} + \nu_t, \qquad Z_t = [T_{G,t}, \Delta BERD_t], \qquad \mathbb{E}(\nu_t \nu_t') = V, \tag{1}$$

where A is the matrix of coefficients, C a vector of constants, Z_t the vector of endogenous variables, and V the variance-covariance matrix of innovations ν_t.

The impulse response is depicted in Figure 1 (Panel A) and shows that a shock in global temperature reduces G7 private R&D spending by about 0.6pp. The impact is quite persistent since it lasts for about ten years.[6] For robustness, we replicate our simple VAR analysis by using (i) BERD growth data for the whole OECD group (Panel B) and (ii) data on Gross Domestic Expenditure on R&D (GERD), which accounts for both business enterprise and government R&D spending (Panels C and D). These additional tests confirm that a global temperature shock negatively affect both private and public productive spending in major advanced economies.[7]

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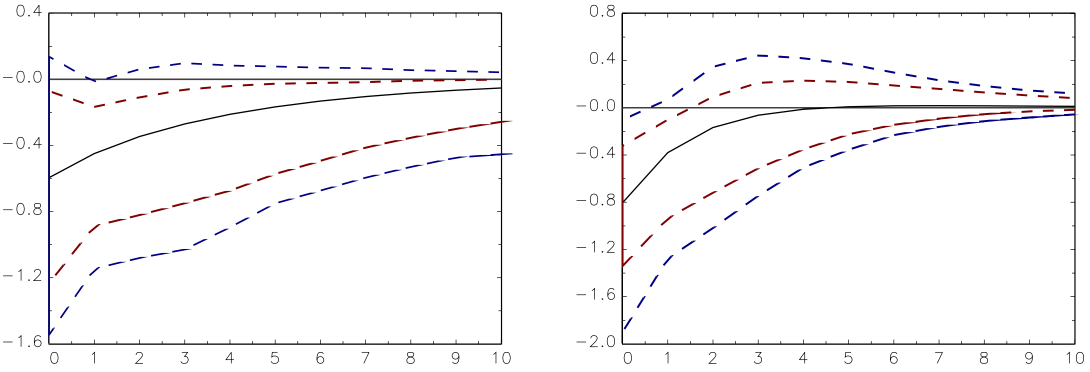
[5] Note that all the R&D growth series are stationary and that the global temperature series is trend-stationary.

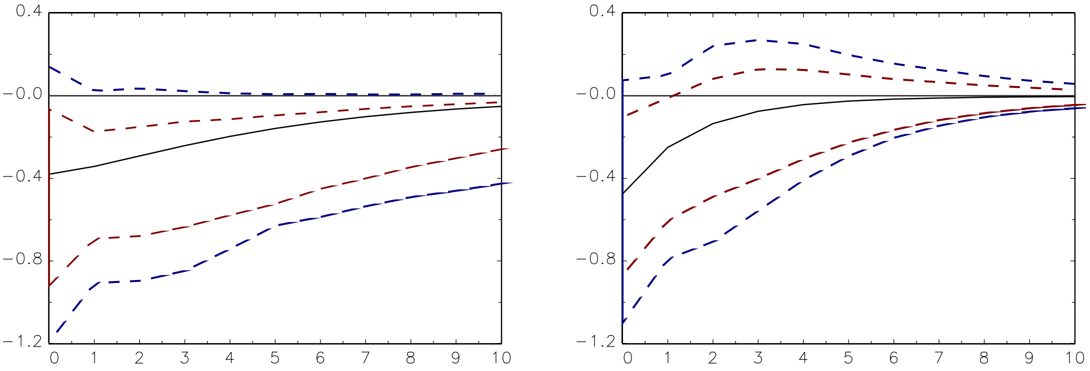
[6] In an additional empirical exercise, we also seek to decipher whether the negative temperature effect on R&D spending is driven by short- or long-run temperature shifts. To this end, we use a linear filter to decompose the temperature variable into the trend and the cyclical component. We then incorporate the two components separately into our VAR analysis. The findings are weaker in terms of significance but lend support to the hypothesis that it is the trend in the recent data which is responsible for the negative effect on R&D expenditure growth in our VAR analysis. Results are not reported here, but available from the authors upon request.

[7] To motivate the ordering of variables with temperature as the most exogenous variable, we perform Granger causality tests using a bivariate VAR(4) model including global mean temperature and R&D expenditure growth in the OECD aggregate. The results suggest a unidirectional significant negative effect at the 10% level going from global temperature to R&D for the measure GERD. This still holds when using the change in global temperature instead. In contrast, R&D does not significantly granger-cause global temperature in any specification. In an additional robustness test, we have computed generalised impulse responses. These provide almost indistinguishable dynamics. Therefore, our results do not rely on the ordering of the variables. Due to space considerations, results are not reported but are available from the authors upon request.

Figure 1: Impulse Response of R&D Expenditure Growth to Global Temperature Shock



Panel A: $T_G \rightarrow \Delta$BERD (G7) Panel B: $T_G \rightarrow \Delta$BERD (OECD)



Panel A: $T_G \rightarrow \Delta$GERD (G7) Panel B: $T_G \rightarrow \Delta$GERD (OECD)

Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a global temperature shock. Impulse responses are obtained by estimating the bivariate VAR(1) model in Equation (1). Solid black lines: estimated impulse responses. Dashed blue lines: 90% bootstrapped confidence bands. Dashed red lines: 68% bootstrapped confidence bands. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Data are annual and span the period from 1981 to 2014.

Next, we exploit the cross-sectional dimension of our panel by first employing a pooled dynamic fixed effects model and then estimating a panel VAR model.

Dynamic panel regressions. In order to further demonstrate the robustness of the relationship between temperature increases and R&D expenditure growth, we employ a dynamic panel regression with country-fixed effects, in the spirit of Colacito, Hoffmann, and Phan (2016). As in our bivariate VAR estimation, we focus on both the G7 group and the whole OECD region. Specifically, we regress BERD and GERD growth in each country on its lagged value and temperature:

$$\Delta R\&D^{j}_{i,t} = c_i + \rho \Delta R\&D^{j}_{i,t-1} + \beta \bar{T}^{k}_{i,t} + \epsilon_{i,t}, \tag{2}$$

where $j \in \{BERD, GERD\}$ and $\bar{T}^k_{i,t}$ a moving average of temperature using a horizon of k years.[8]

As a first step, we use global temperature as the regressor and set $\bar{T}^k_{i,t} \equiv \bar{T}^k_{G,t}$. This specification is similar to the panel analysis of Bansal and Ochoa (2011a), who also use global temperature as the regressor. As a further check, we follow Colacito, Hoffmann, and Phan (2016) and use country-specific temperature levels in a second set of estimations.

Regression results for the G7 countries, the OECD countries, and the OECD plus additional countries (OECD+) are reported in Table 1. Panels A and B report estimation results using global temperature as regressor. Except for the OECD+ countries using GERD as R&D measure, contemporaneous temperature effects on R&D expenditure growth (using $k = 1$) are always significantly negative, at least at the 5% level. Panel estimations also confirm that the effect of an increase in global temperature on R&D expenditure is larger for the group of OECD countries than for the G7 group, in line with our bi-variate VAR analysis above. Why this is the case is slightly puzzling to us, but we hypothesise that smaller (yet developed) countries (i.e. countries that are members of the OECD but not members of the G7 group) are more vulnerable to changes in global temperature than larger countries (i.e. the G7 countries), since the G7 countries can probably be considered to be (on average) richer than the other OECD countries. Thus, this finding would be in line with the empirical evidence of Dell, Jones, and Olken (2012) that poorer countries are more exposed to temperature risk than richer countries.

Using moving averages of global temperature with horizons k larger than one does not improve results, but they still hold. Since global temperature is already a cross-sectional average of regional temperature, to a large extent, noise in the time-series that is not related to changes in the climate are already filtered out. Therefore, changes in global temperature seem to be best at capturing the adverse effects of climate changes.

In Panels C and D, where we use country-specific temperature levels, contemporaneous temperature effects on R&D expenditure ($k = 1$) are still found to be negative but at lower significance levels. Whereas increases in global temperature already indicate changes in the

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[8] We performed a Hausman test using Equation (2) without the lagged depended variable to check whether the fixed effects model produces significantly different estimators compared to a random effects model. Results (available upon request) suggest that the fixed effects model should be preferred. Moreover, using unit root tests, we have checked that these R&D expenditure growth rates are stationary. Hence, we do not need to test for a cointegration relationship between the variables in our panel regressions, since there cannot be one.

Table 1: Effects of Global and Country-specific Temperature on R&D Expenditure

Panel A: $\Delta BERD$ vs. $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-4.236**	-11.435***	-8.806**
	(0.015)	(0.002)	(0.016)
k = 3yrs	-3.439*	-10.704**	-7.354
	(0.077)	(0.018)	(0.107)
k = 5yrs	-4.076**	-10.862***	-8.115**
	(0.027)	(0.005)	(0.042)

Panel B: $\Delta GERD$ vs. $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-3.158**	-3.689**	-2.348
	(0.024)	(0.022)	(0.207)
k = 3yrs	-2.315*	-3.571**	-1.066
	(0.060)	(0.024)	(0.627)
k = 5yrs	-2.625**	-4.567***	-2.357
	(0.035)	(0.004)	(0.276)

Panel C: $\Delta BERD$ vs. $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-0.487	-0.895	-0.393
	(0.157)	(0.111)	(0.519)
k = 3yrs	-1.759***	-3.010***	-2.052**
	(0.001)	(0.000)	(0.027)
k = 5yrs	-1.905***	-3.403***	-2.579**
	(0.005)	(0.001)	(0.016)

Panel D: $\Delta GERD$ vs. $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-0.383	-0.508	-0.134
	(0.215)	(0.150)	(0.739)
k = 3yrs	-0.915**	-1.410**	-0.769
	(0.029)	(0.045)	(0.286)
k = 5yrs	-1.137**	-1.360*	-0.743
	(0.021)	(0.053)	(0.323)

Notes: Panels A and B report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of global temperature $\bar{T}_G^k$, according to Equation (2). Panels C and D report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of country-specific temperature $\bar{T}_i^k$. The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

temperature trend, this is not the case for country-specific temperature. Therefore, by using moving averages of local temperature with larger horizons k, we can filter out short-run weather fluctuations and isolate shocks to the temperature trend which represent long-run temperature risks associated with global warming (see also Bansal, Kiku, and Ochoa, 2016). The results demonstrate that the larger the horizon k, the more pronounced are the adverse temperature effects. They are also significant at least at the 10% level (except for the OECD+ countries using GERD as R&D measure).

Panel VAR. Since the bivariate VAR does not account for the cross-sectional dimension and as the fixed effect estimation results reported in Table 1 may be subject to a simultaneous equation bias from the endogeneity between the error term and the lagged dependent variable, we estimate a panel vector autoregressions model (Panel VARs). They have the same structure as VAR models but add a cross-sectional dimension, and they can account for the bias of a pooled dynamic fixed effects model. Therefore, 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.[9]

We estimate a panel VAR using global temperature data and G7 and OECD R&D expenditure growth data using the PVAR package provided by Abrigo and Love (2016). Specifically, the bivariate homogeneous panel VAR of order 1 with panel-specific fixed effects is represented by the following system of linear equations:

$$Y_{i,t} = A_1 Y_{i,t-1} + u_i + e_{i,t}, \tag{3}$$

where the (1×2) vector of dependent variables $Y_{i,t}$ includes the global temperature level $T_{G,t}$ and the growth rate of R&D expenditure $\Delta R\&D_t$ (either measured by $BERD$ or by $GERD$); u_i and $e_{i,t}$ are (1×2) vectors of dependent variable-specific panel fixed-effects and idiosyncratic errors, respectively. The model is estimated by the Generalised Method of Moments (GMM), and we use the first four lags of the dependent variables as instruments.

By computing orthogonalised impulse responses, we find significant evidence that a global temperature shock undermines R&D expenditure for both regions (G7 and OECD countries) and both R&D measures (see Figure 2). More specifically, an increase in global temperature has

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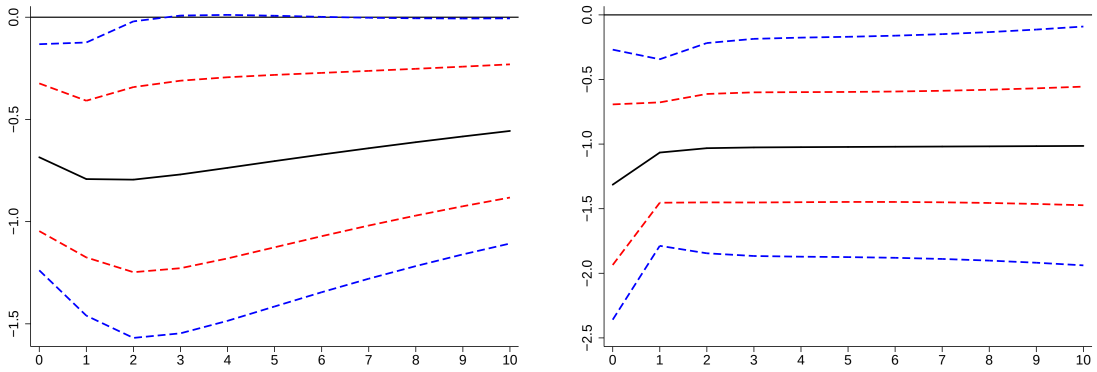
[9] See Canova and Ciccarelli (2013) for a detailed overview of panel VARs.

Figure 2: Impulse Response of R&D Expenditure Growth to a Global Temperature Shock (Panel VAR)

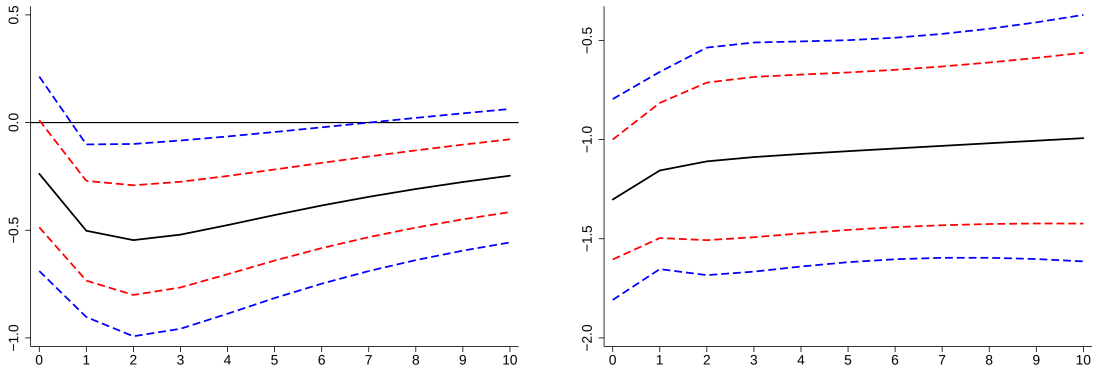


Panel A: $T_G \rightarrow \Delta BERD(G7)$

Panel B: $T_G \rightarrow \Delta BERD(OECD)$

Panel A: $T_G \rightarrow \Delta GERD(G7)$

Panel B: $T_G \rightarrow \Delta GERD(OECD)$



Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a global temperature shock. Impulse responses are obtained by estimating a bivariate Panel-VAR(1) according to Equation (3) using the Generalised Method of Moments (GMM) where global temperature is ordered first. The lag order of the dependent variables to be used as instruments is chosen to be four. The Panel-VAR satisfies stability conditions. Solid black lines: estimated impulse responses. Dashed blue lines: 90% confidence bands obtained by Monte Carlo draws. Dashed red lines: 68% confidence bands obtained by Monte Carlo draws. Robust standard errors are computed by clustering standard errors at the country level. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Data are annual and span the period from 1981 to 2014.

a contemporaneous negative effect which lasts for several years following the shock.

3.2 Robustness

Temperature growth. As a first robustness test, we use global temperature growth (instead of global temperature level) in our bivariate VAR analysis. We therefore compute the impulse response of R&D expenditure growth to a shock in global temperature growth. The results for both the G7 and OECD group are reported in Appendix B and demonstrate that a shock to global temperature growth produces a drop in $\Delta BERD_t$ and $\Delta GERD_t$ of similar size. However, the effect is less persistent and less statistically significant in all cases (see Figure B.1).

As in our bivariate VAR analysis above, we also test whether our panel results still hold if we use the changes in rather than the level of global temperature. The estimation equation hence reads

$$\Delta R\&D^{j}_{i,t} = c_i + \rho \Delta R\&D^{j}_{i,t-1} + \beta \Delta T_{G,t} + \epsilon_{i,t}. \tag{4}$$

Results are reported in Appendix B, Table B.1, and show that temperature effects on both BERD and GERD R&D growth are still significant when using the first difference of global temperature as regressor.

Arellano-Bond estimation. We acknowledge that the fixed effect estimation results reported in Table 1 may be subject to a simultaneous equation bias from the endogeneity between the error term and the lagged dependent variable. We account for this by performing our dynamic panel regressions using Equation (2) by means of the unbiased Arellano-Bond estimator. The results, reported in Table B.2, suggest that our main results are basically unchanged. Using the measure $\Delta BERD_t$, there are sill significant adverse effects of global temperature increases on R&D expenditure in the two larger country groups (OECD and OECD+). For larger horizons k, the country-specific temperature effects become stronger and significant for most specifications. This suggests that the simultaneous equation bias is minimal for these data and that we may use the dynamic fixed effects estimator for efficiency reasons.

Controlling for the global financial crisis. As an additional robustness test, we include a dummy variable which captures the effect of the global financial crisis on R&D expenditure growth. This takes into account that the temperature effect might be biased upwards due to its potential (spurious) correlation with the business cycle, which is unaccounted for in the empirical model. The estimated equation is given by Equation (2) plus the additional control variable:

$$\Delta R\&D^{j}_{i,t} = c_i + \rho \Delta R\&D^{j}_{i,t-1} + \beta \bar{T}^{k}_{i,t} + \alpha \texttt{CRISIS}_t + \epsilon_{i,t}, \tag{5}$$

where $\texttt{CRISIS}_t$ represents the financial crisis dummy that equals one for the years 2008 and 2009 (and zero otherwise).

Results are reported in Appendix B, Table B.3. Again, increases in contemporaneous global temperature and in the moving average of local temperature with larger horizons k still significantly harm R&D expenditure growth.

Controlling for GDP (consumption) growth. Similar to controlling for the effect of the global financial crisis, we include a control variable which captures the effect of the business cycle on R&D expenditure. This takes into account that the temperature effect might be biased upwards due to its potential (spurious) correlation with GDP or consumption growth, which is unaccounted for in the empirical model. The estimated equation is given by Equation (2) plus the additional macroeconomic control variable:

$$\Delta R\&D^{j}_{i,t} = c_i + \rho \Delta R\&D^{j}_{i,t-1} + \beta \bar{T}^{k}_{i,t} + \alpha \texttt{Macro}_t + \epsilon_{i,t}, \tag{6}$$

where $\texttt{Macro}_t$ represents either GDP or consumption growth.

Results are reported in Appendix B, Tables B.4 and B.5. When controlling for GDP or consumption growth, temperature effects are still found to be negative, but our estimates become less significant overall. However, for the measure BERD and the region OECD, temperature effects are still significant.

"Warmer" vs. "cooler" countries. Temperature effects on R&D may also depend on the country's climate, since relatively warmer countries typically have a larger agricultural sector which is more vulnerable to changing weather conditions compared to other sectors in the economy. Bansal and Ochoa (2011a) show that temperature effects on equity returns are larger for countries closer to the equator, since they are more exposed to temperature changes. In a panel analysis on the U.S. states, Colacito, Hoffmann, and Phan (2016) show that adverse effects of temperature changes on GDP growth are substantially larger in the southern states (i.e. warmer states). To account for heterogeneous temperature effects on R&D, we estimate Equation (2) again but divide the largest sample available (OECD+) into relatively warmer and relatively cooler countries. In line with the literature, we observe that an increase in both global and country-specific temperature has a larger impact on "warmer" countries (see Table B.6).

Random-coefficients model. As mentioned in the previous robustness check, one might suspect a violation of the homogeneity assumption in our previous panel estimations. Climate effects can be heterogeneous, since the sensitivity to weather conditions can be different across countries. To further account for this, we use the random-coefficients model proposed by Swamy

(1970). The estimated equation is given by:

$$y_{i,t} = X_i \beta_i + \epsilon_{i,t}, \tag{7}$$

where β_i is the coefficient vector for the ith cross-sectional unit, such that $\beta_i = \beta + v_i$, $\mathbb{E}(v_i) = 0$, and $\mathbb{E}(v_i v_i') = \Sigma$. Hence, the parameter vector β_i is a realization of a stochastic process, and the coefficients are allowed to vary across the cross-sectional units. Again, we regress the growth rate of BERD (GERD) R&D expenditure on its lagged value and the moving average of global (country-specific) temperature. The random-coefficients model produces similar estimates compared to our benchmark dynamic fixed effects regression with results pointing to significant negative temperature effects on R&D expenditure growth rates (see Table B.7). This suggests that heterogeneity is not a severe issue in our data.[10]

Additional panel VAR impulse responses. In the previous section, the panel VAR was estimated using global temperature level data alone. In this section, as a last robustness check, we additionally look at the impulse response functions when we use country-specific instead of global temperature and first differences instead of the level of temperature.

Using country-specific temperature, the results are less significant, but they still indicate that changes in local temperature have a delayed (and negative) effect on R&D expenditure growth. For the OECD region, we find that an increase in local temperature significantly affects R&D expenditure growth one year after the shock (see Figure B.2). As global temperature is trend-stationary, we also show impulse responses of R&D expenditure growth following a shock to the first difference in the global temperature level to confirm the negative relationship between temperature and R&D (see Figure B.3). Results indicate that temperature changes still produce a statistically significant drop in R&D expenditure growth for most specifications, but the decline is less persistent. As a final test, we check whether our results still hold if we add GDP or consumption growth as an additional endogenous variable to control for business cycle dynamics that may be correlated with temperature.[11] Again, for most specifications,

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[10] As for our dynamic fixed effects model, our estimates from the random-coefficients model are subject to the simultaneous equation bias from the endogeneity between the error term and the lagged dependent variable.

[11] In this case, we only plot impulse responses for the OECD region, as the number of clusters are too small to compute robust standard errors given the larger number of instruments to be estimated when using the G7 countries. Moreover, global temperature enters the Panel VAR as first difference, since the trend in the level series now leads to explosive impulse responses.

temperature adversely affects R&D expenditure growth (see Figures B.4 and B.5).

3.3 Summary

Taken together, our empirical results suggest that increases in both global and country-specific temperature harm aggregate R&D expenditure. Moreover, these adverse effects are found to be long-lasting. As only multi-country aggregate R&D expenditure data are available, the economic channels through which temperature affects R&D expenditure growth have yet to be identified. In light of the empirical evidence brought forward by a number of studies that an increase in temperature reduces both the levels and the growth rates of output and consumption, as well as total factor productivity and labour productivity growth (e.g., Bansal and Ochoa, 2011b; Dell, Jones, and Olken, 2012; Deryugina and Hsiang, 2014; Donadelli, Jüppner, Riedel, and Schlag, 2017), we hypothesise that the decrease in R&D expenditure is mainly due to an aggregate distribution effect. Specifically, we hypothesise that if there is less output produced or output growth slows down due to global warming, there will be fewer resources available to be invested in R&D. As we find weaker effects when we control for GDP and consumption growth in our econometric setups, we take this as evidence for the existence of this channel.

This argument is closely related to the capital accumulation effect proposed by Fankhauser and Tol (2005). The authors also suggest the presence of a savings effect according to which forward-looking agents change their savings behaviour to respond to the negative impact of future climate change. This suppresses growth prospects and investments further, which would as well limit the resources available for R&D expenditures.

However, there must also be another channel since our robustness tests have shown that we still find a negative effect of changes in temperature on R&D expenditure even after controlling for GDP or consumption growth. For example, Deryugina and Hsiang (2014) suggest that it is the lower productivity of workers and crops at higher temperatures that drives the negative effect of a rise in temperature on macro aggregates. R&D departments and inventors are thus also probably less productive at high temperatures and consequently might receive less funding.

In the next section, we rationalise these empirical findings within a stochastic endogenous growth model in which R&D expenditure drives economic growth in order to quantify the effects of temperature shocks on macroeconomic quantities, asset prices, and welfare.

4 The Model

In this section, we develop a stochastic endogenous growth model with a government sector that features global temperature dynamics as in Bansal and Ochoa (2011b) or Donadelli, Jüppner, Riedel, and Schlag (2017). We assume that temperature risk has an impact on the real economy via its contribution to the depreciation risk of patents. Our model allows us to reproduce the adverse effects of temperature shocks on R&D expenditure growth and the real economy, as observed in the data.

Representative household. The representative household is equipped with Epstein and Zin (1989) preferences over the utility flow u_t:

$$U_t = \left[(1-\beta) u_t^{1-\frac{1}{\psi}} + \beta \left(\mathbb{E}_t[U_{t+1}^{1-\gamma}] \right)^{\frac{1-1/\psi}{1-\gamma}} \right]^{\frac{1}{1-1/\psi}}, \tag{8}$$

where γ is relative risk aversion, ψ determines the elasticity of intertemporal substitution, and β is the time discount factor. The utility flow is given by:

$$u_t = C_t^* (\overline{L} - L_t)^{\tau}, \tag{9}$$

where C_t^* defines total consumption of the final good (after subtracting government lump-sum taxes), $\overline{L} - L_t$ represents leisure (total time endowment less labour supply), and τ determines the elasticity of labour supply. The budget constraint of the household reads:

$$C_t^* = C_t + \tau_c G_t = (1 - \tau_{l,t}) W_t^u L_t + \tau_c G_t + D_{a,t} - S_t, \tag{10}$$

where W_t^u denotes the frictionless wage, L_t is the amount of labour supplied by the household, $\tau_{l,t}$ is the time-varying labour income tax rate, $\tau_c G_t$ is the total amount of a government-levied lump-sum tax on the household (whereby τ_c is the fraction of total government expenditure G_t that is financed by the household with this lump-sum tax)[12], C_t represents consumption of the household before government taxation, $D_{a,t}$ is aggregate dividends, and S_t is the economy's total

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[12] To make this a tax, $\tau_c < 0$ has to be assumed. Since we find in our quantitative analysis later that a lump-sum tax is welfare-improving (but not a consumption transfer), the case of a tax, i.e. $\tau_c < 0$, is the only relevant case studied in this paper.

R&D expenditure. The household's stochastic discount factor (SDF) is:

$$\mathbb{M}_{t,t+1} = \beta \left(\frac{u_{t+1}}{u_t}\right)^{1-\frac{1}{\psi}} \left(\frac{C^*_{t+1}}{C^*_t}\right)^{-1} \left(\frac{U_{t+1}}{\mathbb{E}_t[U_{t+1}^{1-\gamma}]^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma}. \tag{11}$$

The optimal labour supply is determined by the following condition:

$$(1-\tau_{l,t})W^u_t = \frac{\tau C^*_t}{\bar{L} - L_t}. \tag{12}$$

As in Uhlig (2007), we assume that only a fraction of the optimal labour supply reaches the market, which results in sticky wages. Formally:

$$W_t = (e^{\Delta n_t} W_{t-1})^{\mu} (W^u_t)^{1-\mu}, \tag{13}$$

where $\mu \in [0,1]$ measures the degree of labour market frictions while $\Delta n_t = \ln(N_t/N_{t-1})$ captures technology growth as will be explained in Equation (31).[13]

Final goods sector. The representative final goods firm produces the output according to:

$$Y_t = (K_t^{\alpha}(A_t L_t)^{1-\alpha})^{1-\xi} \Xi_t^{\xi}, \quad \Xi_t = \left[\int_0^{N_t} X_{i,t}^{\nu}\, di\right]^{\frac{1}{\nu}}, \tag{14}$$

where α determines the capital share, ξ is the share of intermediate goods, and ν is the elasticity of substitution between intermediate goods in the bundle Ξ_t. The total number of intermediate goods or patents in the economy is N_t. Stochastic productivity shocks are induced by the process A_t with dynamics:

$$A_t = e^{a_t}, \quad a_t = \rho_a \cdot a_{t-1} + \varepsilon_{a,t}, \tag{15}$$

where ρ_a determines the persistence of productivity shocks and $\varepsilon_{a,t} \sim \mathcal{N}(0, \sigma_a)$. The final goods firm maximises its shareholder value by optimally choosing total capital investment I^*_t, labour L_t, next period's capital K_{t+1}, and the demand for intermediate good i, denoted by $X_{i,t}$:

$$\max_{\{I^*_t, L_t, K_{t+1}, X_{i,t}\}_{t\geqslant 0, i\in[0,N_t]}} \mathbb{E}_0\left[\sum_{t=0}^{\infty} \mathbb{M}_{0,t} D_t\right], \tag{16}$$

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[13] The inclusion of wage rigidities into the model is only done for quantitative purposes, i.e. so that the benchmark model matches the asset pricing and some macroeconomic moments better. Qualitatively, nothing would change if we assumed the absence of wage rigidities.

subject to the definition of the final goods firm's dividends and the capital accumulation equation:

$$D_t = Y_t - I_t - W_t L_t - \int_0^{N_t} P_{i,t} X_{i,t} \, di, \tag{17}$$

$$K_{t+1} = (1-\delta)K_t + \Lambda\left(\frac{I_t^*}{K_t}\right) K_t, \tag{18}$$

where $P_{i,t}$ is the price of intermediate good i, δ is the capital depreciation rate, and $\Lambda\left(I_t^*/K_t\right) = \frac{\alpha_1}{1-1/\zeta}\left(I_t^*/K_t\right)^{1-1/\zeta} + \alpha_2$ is the adjustment cost function transforming investment in new capital, as in Jermann (1998). The constants α_1 and α_2 are calibrated such that adjustment costs are zero in the deterministic steady state.

Moreover, the government subsidises capital investment by transferring a fraction τ_i of total government expenditure to the final goods firm. This implies that only a fraction of total capital investment I_t^* has to be supplied by the final goods firm, i.e. $I_t = (1-\tau_{inv,t})I_t^*$. The remaining fraction $\tau_{inv,t}$ is paid as a subsidy by the government. In particular, it holds that $\tau_i G_t = \tau_{inv,t} I_t$. The resulting equilibrium conditions are as follows:

$$\frac{1-\tau_{inv,t}}{\Lambda'\left(\frac{I_t^*}{K_t}\right)} = \mathbb{E}_t\left[\mathbb{M}_{t,t+1}\left\{\frac{(1-\xi)\alpha Y_{t+1} - (1-\tau_{inv,t+1})\, I_{t+1}^*}{K_{t+1}} + \frac{(1-\tau_{inv,t+1})\left(\Lambda\left(\frac{I_{t+1}^*}{K_{t+1}}\right) + 1 - \delta\right)}{\Lambda'\left(\frac{I_{t+1}^*}{K_{t+1}}\right)}\right\}\right], \tag{19}$$

$$W_t = \frac{(1-\xi)(1-\alpha)Y_t}{L_t}, \tag{20}$$

$$X_{i,t}(P_{i,t}) = \left(\frac{\xi Y_t}{P_{i,t}}\right)^{\frac{1}{1-\nu}} \Xi_t^{\frac{\nu}{\nu-1}}. \tag{21}$$

Intermediate goods sector. Each intermediate good $i \in [0, N_t]$ is produced by an atomistic, monopolistically competitive firm facing the following maximization problem:

$$\max_{\{P_{i,t}\}} \{\Pi_{i,t}\} = \max_{\{P_{i,t}\}} \{P_{i,t} X_{i,t}(P_{i,t}) - X_{i,t}(P_{i,t})\}. \tag{22}$$

A symmetric equilibirum is obtained by solving the maximization problem (22):

$$P_{i,t} \equiv P_t = \frac{1}{\nu}, \tag{23}$$

$$\Pi_{i,t} \equiv \Pi_t = \left(\frac{1}{\nu} - 1\right) X_t, \tag{24}$$

$$X_{i,t} \equiv X_t = \left(\xi\nu(K_t^{\alpha}(A_t L_t)^{1-\alpha})^{1-\xi} N_t^{\frac{\xi}{\nu}-1}\right)^{\frac{1}{1-\xi}}. \tag{25}$$

Substituting Equation (25) into the production function (14) and imposing the following restriction to ensure balanced growth, i.e. $1-\alpha = (\xi/\nu - \xi)/(1-\xi)$, implies:

$$Y_t = (\xi\nu)^{\frac{\xi}{1-\xi}} K_t^{\alpha}(A_t N_t L_t)^{1-\alpha}. \tag{26}$$

Finally, the value $V_{i,t} \equiv V_t$ of owning exclusive rights to produce intermediate good i using the respective patent i is equal to the present value of the current and future monopoly profits:

$$V_{i,t} \equiv V_t = (1-\tau_\pi)\Pi_t + \kappa_t \mathbb{E}_t[\mathbb{M}_{t,t+1} V_{t+1}], \tag{27}$$

where τ_π is the constant tax rate levied by the government on the profits of intermediate goods firms and the firm (patent) survival probability κ_t is given by:

$$\kappa_t = e^{\theta_t}(1-\phi). \tag{28}$$

We assume that the depreciation rate of patents $1-\kappa_t$ is stochastic by applying the following stochastic process:[14]

$$\theta_t = \rho_\theta \theta_{t-1} + \tau_T \varepsilon_{T,t}. \tag{29}$$

In the absence of depreciation shocks, ϕ is the probability that a patent becomes obsolete. The parameter τ_T measures the sensitivity of the obsolescence rate to temperature shocks and ρ_θ measures the persistence of these depreciation shocks.[15] We capture global warming effects by assuming that unexpected changes in the obsolescence rate are induced by temperature shocks.[16] As a potential channel of how temperature shocks affect the accumulation of patents, one can think of non-green ("dirty") technologies becoming obsolete due to climate change, which

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[14] In this respect, we are close to Furlanetto and Seneca (2014), who introduce a stochastic depreciation rate into a standard New Keynesian model.

[15] For parsimony, we only focus on temperature shocks as a source of depreciation risk and do not introduce a shock component, i.e. $\sigma_\theta \epsilon_\theta$, in Equation (29). Simulations including the latter confirm that this additional source of risk does not materially affect our quantitative results.

[16] In Section 7, we also study the quantitative implications of the case that deviations from the long-run mean of temperature, i.e. $T_t - \mu_T$, affect the patent obsolescence rate instead of the temperature shocks $\varepsilon_{T,t}$ themselves. Moreover, we investigate how large the effects of temperature risk are if they affect labor productivity instead of patent obsolescence. We find qualitatively similar results in these two cases.

reduces productivity in the economy. We calibrate the sensitivity parameter τ_T such that the model matches the magnitude of the negative effects of temperature shocks on R&D expenditure growth observed in the data.

Temperature dynamics. As in Bansal and Ochoa (2011b) and Donadelli, Jüppner, Riedel, and Schlag (2017), global temperature T_t evolves according to:

$$T_t = \mu_T + \rho_T (T_{t-1} - \mu_T) + \varepsilon_{T,t}, \tag{30}$$

where ρ_T is the persistence parameter, μ_T is the long-run mean of global temperature, and $\varepsilon_{T,t} \sim \mathcal{N}(0, \sigma_T)$.

Innovation sector. The number of intermediate goods N_t evolves according to:

$$N_{t+1} = \vartheta_t S_t^* + \kappa_t N_t, \tag{31}$$

where S_t^* denotes the economy's R&D expenditure. This expenditure is the sum of firm investment in R&D, denoted by S_t, and government subsidies to innovators, given by $\tau_s G_t$. This total amount of government R&D subsidies satisfies the following condition:

$$\tau_s G_t = \tau_{rd,t} S_t^*, \tag{32}$$

so that $\tau_{rd,t}$ measures the fraction of the economy's total R&D expenditure supplied by the government. The innovation sector's productivity ϑ_t that is taken as given by innovating firms has the functional form:

$$\vartheta_t = \chi \left(\frac{S_t^*}{N_t} \right)^{\eta - 1}, \tag{33}$$

where χ is the R&D productivity shift parameter, and η determines the elasticity of R&D investment.[17]

The payoff to innovation is the expected value of discounted future profits on a patent (i.e.

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[17] An alternative way of modelling temperature effects in this setup is to let temperature shocks affect the R&D productivity shift parameter χ instead of the obsolescence rate of patents ϕ. Simulations show that the two specifications produce similar impulse responses.

$\mathbb{E}_t[\mathbb{M}_{t,t+1}V_{t+1}])$. Thus, free entry into the innovation sector implies:

$$\mathbb{E}_t[\mathbb{M}_{t,t+1}V_{t+1}]\,(N_{t+1} - \kappa_t N_t) = (1 - \tau_{rd,t})S_t^*, \tag{34}$$

which states that the expected sales revenues equal the innovation costs.

Government and fiscal policy. The ratio of government expenditure to output G_t/Y_t is exogenously determined by the following stochastic process which ensures that $G_t/Y_t \in (0,1)$:

$$\frac{G_t}{Y_t} = \frac{e^{gy_t}}{1 + e^{gy_t}}, \tag{35}$$

$$gy_t = (1 - \rho_{gy})\overline{gy} + \rho_g gy_{t-1} + \varepsilon_{gy,t}, \tag{36}$$

where $\varepsilon_{gy,t} \sim \mathcal{N}(0, \sigma_g)$, ρ_{gy} determines the persistence of shocks to the government expenditure to output ratio, and $\overline{gy}$ is the long-run mean of the government expenditure to output ratio. For the sake of simplicity, we assume that the government has to comply with a zero-deficit rule and is not allowed to run any fiscal deficits.[18] Therefore, it has to finance its expenditure level each period by taxes. Government spending consists of fiscal transfers and the potential remaining part $Z_t = (1 - \tau_i - \tau_s)G_t$, which is considered as wasteful. Assuming $\tau_i + \tau_s \leqslant 1$ assures that government subsidies are never larger than the total government expenditure. This implies that the government budget constraint is:

$$G_t = -\tau_c G_t + \tau_{l,t} W_t L_t + \tau_\pi N_t \Pi_t = (\tau_i + \tau_s)G_t + Z_t. \tag{37}$$

Furthermore, the labour tax rate is determined by:

$$\tau_{l,t} = \frac{G_t - \tau_\pi N_t \Pi_t + \tau_c G_t}{W_t L_t}. \tag{38}$$

Aggregate resource constraint. Final goods output is used for consumption, production of intermediate goods, capital investment, R&D expenditure, and government spending. Hence,

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[18] In Section 7, we analyse the case that the government is allowed to run fiscal deficits and applies a tax smoothing policy. The results demonstrate that the assumption of a zero-deficit rule does not materially affect our results.

the aggregate resource constraint reads as follows:

$$Y_t = C_t + N_t X_t + I_t + S_t + G_t = C_t^* + N_t X_t + I_t^* + S_t^* + Z_t - \tau_c G_t. \tag{39}$$

Aggregate dividends are given by the sum of the (after-tax) corporate profits of the final goods firm and the continuum of intermediate goods producers:

$$D_{a,t} = D_t + (1 - \tau_\pi) N_t \Pi_t. \tag{40}$$

Asset prices. We study the dynamics of two asset prices in this economy: a risk-free bond and the aggregate market's stock price. First, the risk-free rate solves:

$$r_{f,t} = \ln(R_{f,t}), \quad R_{f,t} = \frac{1}{\mathbb{E}_t[\mathbb{M}_{t,t+1}]}. \tag{41}$$

Second, the aggregate market's stock price, its return, and its risk premium are given by:

$$V_{a,t} = D_{a,t} + \mathbb{E}_t[\mathbb{M}_{t,t+1} V_{a,t+1}], \tag{42}$$

$$R_{a,t} = \frac{V_{a,t}}{V_{a,t-1} - D_{a,t-1}}, \tag{43}$$

$$r_{a,t} - r_{f,t} = (1 + \varphi)(\ln(R_{a,t}) - r_{f,t}), \tag{44}$$

where the aggregate market excess return is levered by imposing $\varphi = 1$ (see Croce, 2014; Gao, Hitzemann, Shaliastovich, and Xu, 2016).

5 Calibration

Parameter values for the benchmark economy are reported in Table 2. To be consistent with our bivariate VAR analysis in Section 3, we calibrate the model to (cross-country average) G7 data and to an annual frequency. We set the standard parameters in line with the literature on long-run risk. As in Kung and Schmid (2015), we set $\beta = 0.984$, $\psi = 1.85$, $\gamma = 10$, $\alpha = 0.35$, and $\delta = 0.08$. We then impose $\eta = 0.8$ in order to obtain a volatility of R&D investments close to the data. To achieve that investment is more volatile than output as in the data, we set the adjustment cost parameter ζ to a value of 0.9. The inverse of the monopoly markup parameter is equal to 1/1.5, which is close to the value used by Kung and Schmid (2015). The long-run mean R&D depreciation rate ϕ is set to 0.09, as in Bena, Garlappi, and Grüning (2016). The wage rigidity parameter μ is set to 0.35, as in Uhlig (2007).

Table 2: MODEL PARAMETER VALUES

Parameter	Description	Value
β	Time discount factor	0.984
ψ	Elasticity of intertemporal substitution	1.85
γ	Relative risk aversion	10
τ	Labour elasticity	1.8173
μ	Sticky wage parameter	0.35
η	R&D investment elasticity	0.80
ν	Inverse monopoly markup	1/1.5
ϕ	Patent obsolescence rate	0.09
τ_T	Impact of temperature shocks on obsolescence of patents	-0.008
ρ_θ	persistence of patent obsolescence shocks	0.95
χ	R&D productivity parameter	2.4682
α	Capital share	0.35
ξ	Intermediate goods share	0.5652
δ	Capital depreciation rate	0.08
ζ	Capital adjustment costs elasticity	0.90
$\overline{gy}$	Long-run mean of government expenditure	-1.6883
τ_π	Corporate tax rate	0.33
τ_i	Government subsidy to final goods firm's capital investment	0.00
τ_c	Consumption lump-sum tax rate	0.00
ρ_a	Productivity shock persistence	0.95
σ_a	Productivity shock volatility	0.0161
ρ_g	Government expenditure shock persistence	0.98
σ_g	Government expenditure shock volatility	0.013
μ_T	Long-run mean of global temperature	14.27
ρ_T	Temperature shock persistence	0.91
σ_T	Temperature shock volatility	0.12

Notes: This table reports the parameters we use in the annual calibration of the model described in Section 4.

The cross-country (G7) average corporate tax rate τ_π is set to 0.33, as suggested by KPMG for the period 2011–2017. In our benchmark calibration, we assume that fiscal policy does not subsidise capital investment or R&D expenditure. Moreover, lump-sum taxes are not levied on households. Therefore, we set $\tau_i = \tau_c = \tau_s = 0$. Loosely speaking, this represents an economy in which policymakers do not care about climate risk. To match the Penn World Table (PWT) data on government spending for the G7 countries, we set the parameters ρ_g, $\overline{gy}$, and σ_g to values of 0.98, -1.6883, and 0.013, respectively. These numbers are also in line with the calibration of Donadelli and Grüning (2017).

The persistence of productivity shocks ρ_a is set to 0.95, as in Kung and Schmid (2015). The volatility of productivity shocks σ_a is set to 0.0161 to match the observed volatility of output in the data. The R&D productivity parameter χ is set to the value 2.4682 so that the log growth rate of output in the deterministic steady state is 1.9 percentage points, given all other parameters. The labour elasticity τ is set to 1.8173 in order to have the household work one-third of its total time endowment in the deterministic steady state, given all other parameters.

The persistence of depreciation shocks is chosen to let the model reproduce the persistent effect of temperature shocks on R&D expenditure growth observed in the data. To this end, we set $\rho_\theta = 0.95$. The parameter τ_T, measuring the impact of temperature shocks on R&D growth, is calibrated to a value of -0.008, which implies in our model that R&D expenditure growth declines by around 0.6pp after an unexpected one standard deviation increase in temperature.

The other parameters regarding temperature dynamics are set to match the global temperature statistics observed in the data over the period 1975–2014. In particular, we set $\mu_T = 14.27$ (degrees Celsius), $\sigma_T = 0.12$, and $\rho_T = 0.91$ to match the long-run mean and volatility of global temperature.[19]

We numerically solve the model by using a third-order perturbation, as provided by the `Dynare++` package. Since it is a growing economy, in order to be able to do so, we first normalise the non-stationary quantities by the number of intermediate goods N.

6 Quantitative Implications

Simulated moments. The main results produced by our benchmark calibration are reported in Table 3, specification [1]. Compared to the economy without temperature effects (specification [2]), we observe that the impact of temperature on the obsolescence rate of patents is responsible for an 18 basis points (bps) increase in the average equity premium and a 16bps increase in excess stock return volatility. Since the agent has a preference for the early resolution of uncertainty, the negative effect of temperature shocks on the economy is priced. The adverse economic effects of temperature shocks are reflected by a negative correlation between R&D expenditure and global temperature at -0.11, consistent with empirical evidence.

Inspecting the mechanism. Impulse responses of macro aggregates to a one standard deviation increase in global temperature are depicted in Figure 3. Unexpected temperature increases are transmitted to the business cycle via their negative effect on the accumulation of

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[19] Note that the value of the persistence parameter ρ_T is as in Bansal and Ochoa (2011b). Moreover, it is in line with the autocorrelation structure of global temperature observed in the data.

Table 3: MODEL VS. DATA: MACROECONOMIC QUANTITIES AND ASSET PRICES

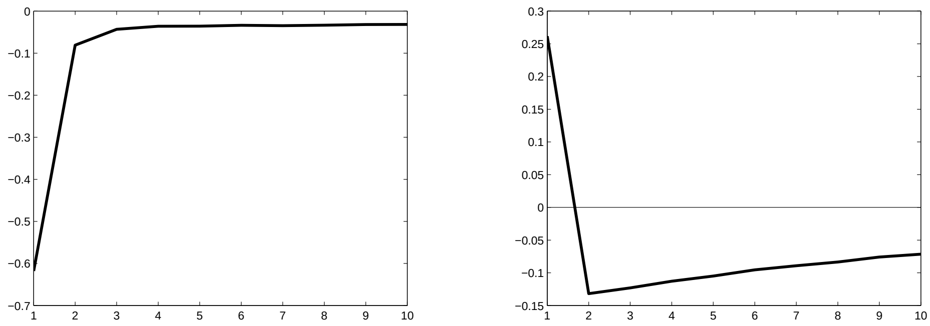
Variable	**Data**	**Benchmark**	$\tau_T = 0$
		[1]	**[2]**
MACRO QUANTITIES			
$\mathbb{E}(\Delta c^*)$	2.25	**2.25**	2.25
$\sigma(\Delta y)$	1.60	**1.60**	1.59
$\sigma(\Delta c^*)$	1.20	**1.14**	1.07
$\sigma(\Delta c^*)/\sigma(\Delta y)$	0.75	**0.71**	0.67
$\sigma(\Delta i^*)/\sigma(\Delta y)$	2.05	**1.05**	1.03
$\sigma(\Delta s^*)/\sigma(\Delta y)$	1.92	**1.95**	1.92
$\rho(\Delta c^*, \Delta y)$	0.87	**0.65**	0.70
$\rho(\Delta c^*, \Delta i^*)$	0.81	**0.66**	0.76
$\rho(\Delta i^*, \Delta y)$	0.93	**0.99**	1.00
$\rho(\Delta s^*, \Delta y)$	0.59	**0.98**	0.99
$\rho(\Delta s^*, T)$	-0.46	**-0.11**	0.00
$\partial \Delta s^* / \partial \varepsilon_T$	-0.57	**-0.62**	0.00
TEMPERATURE			
$\mathbb{E}(T)$	14.27	**14.27**	14.27
$\sigma(T)$	0.23	**0.23**	0.23
ASSET PRICES			
$\mathbb{E}(r_f)$	2.31	**2.32**	2.36
$\sigma(r_f)$	2.88	**0.20**	0.16
$\mathbb{E}[r_a - r_f]$	5.72	**1.49**	1.31
$\sigma(r_a - r_f)$	14.72	**4.63**	4.47

Notes: This table reports the main moments for the benchmark calibration (specification [1]) and the model where temperature does not affect the obsolescence rate of patents (specification [2]), i.e. $\tau_T = 0$ in Equation (29). The aggregate market return is levered as in Croce (2014). Models' entries are obtained from repetitions of small-sample simulations (i.e. averages over 3000 simulations of 41 years). $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot,\cdot)$ denote mean, volatility, and correlation, respectively, and $\partial \Delta s^* / \partial \varepsilon_T$ denotes the initial response of R&D expenditure growth to a one standard deviation shock in temperature in percentage points. Means and standard deviations are also expressed in percentage points. Data on global temperature and G7 macro-aggregates are from the Climate Research Unit and the OECD, respectively. Data are annual and run from 1975 (or later) to 2014. Additional details on the data are provided in Appendix A.

patents. The latter drives the endogenous technical progress and growth in our model. More precisely, positive temperature shocks increase the depreciation of patents today and in the future. Consequently, the adverse and long-lasting effect on the accumulation of patents translates into a persistent decline in productivity growth. This implies that temperature shocks constitute a source of endogenous long-run productivity risk.

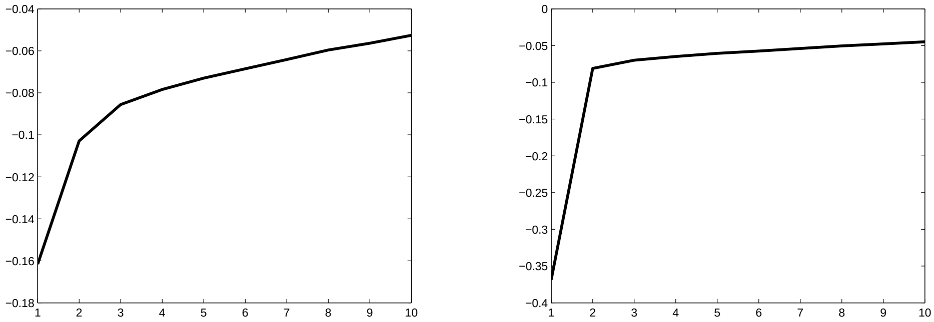
It is worth noting that the decrease in productivity triggers both a substitution and an income effect on macro variables. On the one hand, lower productivity decreases the opportunity costs of consumption such that the agents want to immediately reduce labour and investments in both R&D and capital in order to increase consumption today. On the other hand, the decline in productivity decreases the income of agents, which results into long-lasting losses in output, investments in both R&D and capital, and consumption. Moreover, future labour supply has to

Figure 3: Impulse Responses of Macro Aggregates to Temperature



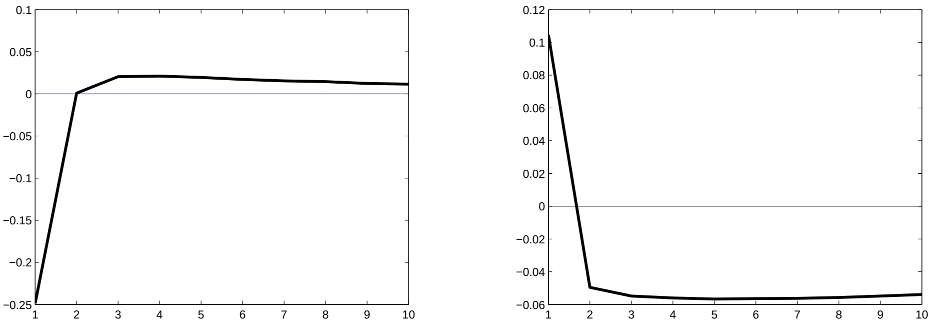
Panel A: $T \to \Delta S^*$

Panel B: $T \to \Delta C^*$



Panel C: $T \to \Delta Y$

Panel D: $T \to \Delta I^*$



Panel E: $T \to \Delta L$

Panel F: $T \to \Delta K$

Notes: This figure reports impulse responses (expressed as deviations from the steady state in percentage points) for a length of 10 years of R&D expenditure growth ΔS^*, consumption growth ΔC^*, output growth ΔY, investment growth ΔI^*, labour growth ΔL, and capital growth ΔK, with respect to a positive one standard deviation temperature shock ($\varepsilon_T > 0$). All the parameters are calibrated to the values reported in Table 2.

be increased in order to compensate for lower productivity. Finally, the persistent adverse effects on the accumulation of patents also harms the accumulation of capital. The impulse response of physical capital is positive on impact since the immediate fall of investment reduces capital one period later, in accordance with the capital accumulation process.

Long-run effects of temperature shocks. To quantify the long-run effects of temperature increases, we calculate expected losses in output growth for horizons from 1 to 50 years ahead after a temporary positive shock to global temperature. To this end, we compare the cumulative growth in an economy in which temperature negatively affects the obsolescence rate of patents to cumulative growth to an economy without temperature risk. The shock sizes are one and two standard deviations of temperature changes, i.e. 0.12°C and 0.24°C, respectively.

Table 4: Long-run Effects of Temperature Shocks

Panel A: Single Transitory Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_T	−0.16	−0.50	−0.80	−1.18	−1.59
2 std. dev. σ_T	−0.32	−1.00	−1.60	−2.37	−3.18
Panel B: Multiple Transitory Shocks — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1981–2014	1981–2030			
obs. shocks 1981–2014	−0.99	−2.60			
Panel C: Permanent Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	16Y				
0.379°C	−9.97				

Notes: Panel A of this table reports the cumulative change in output growth over 1, 5, 10, 20, and 50 years in percentage points after a single temporary temperature shock. The cumulative growth in an economy without such a shock is compared to that in an economy with shocks to temperature (i.e. with $\varepsilon_t > 0$). Specifically, we report $(\sum_{j=1}^{N} \Delta y_{t+j}) - N \cdot \Delta y^*$ where Δy_{t+j} is the log growth rate of total output, and Δy^* is the steady state growth rate in the economy without a shock (i.e. with $\varepsilon_t = 0$). For example, the entry −0.50 for a horizon of 5 years in the first row means that cumulative output growth over these 5 years has been 0.50 percentage points lower than it would have been without the temperature shock. The amount of lost output growth is reported for temperature shocks amounting to one and two standard deviations, i.e. to 0.12°C and 0.24°C, respectively. Panel B reports the cumulative change in output growth if the observed shocks to global temperature (both positive and negative shocks) in the period 1981–2014, backed out from the data by using the definition $\varepsilon_{T,t} = T_{G,t} - T_{G,t-1}$, are used in the model simulation. For the entry under the heading "1981–2030", it is assumed that there are no shocks after 2014. Therefore, the additional cumulative change in output growth is due to the persistent effects of temperature shocks on the patent obsolescence rate that still affect the model years 2014–2030. Panel C reports the cumulative change in output growth for a period of 16 years after a permanent global temperature shock, translating into a permanent increase of the patent obsolescence rate (i.e. we assume $\rho_\theta = 1$). The observed global temperature change, used as the permanent shock, is calculated by subtracting the average global temperature for the first 10 years of the data (1981–1990) from the average global temperature of the last 10 years of data (2005–2014). This calculation gives rise to a change in global temperature of 0.379°C.

Results for expected output growth losses are reported in Table 4, Panel A. After half a century, a single initial temperature shock decreases cumulative output growth by 1.59pp. If the size of the temperature shock is twice as high, growth losses are doubled as well and amount to 3.18pp. The estimates in Table 4 may appear to be small, but one should keep in mind that our exercise is based on a single temperature shock only and does not take into account a possible accumulation of several positive temperature increases over the next century.

Two more results are reported in Table 4. First, in Panel B, we back out the shocks from the observed global temperature series for the period 1981–2014 by defining the shocks $\varepsilon_{T,t}$ as the difference between the global temperature in year t and year $t-1$, i.e. $\varepsilon_{T,t} = T_{G,t} - T_{G,t-1}$.[20] Next, we feed these shocks into the model simulation. We then again compare the cumulative growth of the economy with these shocks to the economy without any temperature shocks. First, we just compute the amount of growth lost for the period 1981–2014 and find that 0.99pp of output growth is lost over these 34 years. We also continue the model simulation for another 16 years (i.e. until 2030) and assume there are no further temperature shocks. The larger negative effect of -2.60pp is thus due to the assumed persistence of temperature shocks on the patent obsolescence rate. Second, Panel C reports how much growth is lost over a period of 16 years if the shock to global temperature (and the patent obsolescence rate) is permanent.[21] In other words, we assume $\rho_\theta = 1$. In light of the discussion in Donadelli, Jüppner, Riedel, and Schlag (2017), this assumption can be interpreted as assuming that the economy does not adapt to the higher temperature level at all. This is in contrast to previous analyses, where shocks to the patent obsolescence rate are assumed to be transitory, and thus the economy is assumed to ultimately adapt to the higher temperature level. Therefore, the observed negative effect in the model is naturally much larger and amounts to 9.97pp over a period of just 16 years.

Welfare costs. Following Croce, Kung, Nguyen, and Schmid (2012), welfare costs are defined as the percentage increase of time-zero utility bundle units Δ that one must give to the household in order to make it indifferent between the utility bundle process of the benchmark calibration $\{u\}$ and the utility bundle process of the economy without temperature effects $\{u^*\}$:

$$e^{\hat{U}} = (1+\Delta)e^{\hat{U}^*}, \tag{45}$$

where $\hat{U}$ denotes the natural logarithm of the ratio of the utility index U to the initial number of intermediate goods N.

Table 5 reports welfare costs for temperature effects in the benchmark economy. In our

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[20] The global temperature time series is depicted in Figure A.1.

[21] The size of the permanent shock is chosen to be +0.379°C since calculations using the observed global temperature series reveal that the average global temperature over the last 10 years is 0.379°C higher than the average global temperature in the period 1981–1990.

Table 5: WELFARE COSTS OF TEMPERATURE RISK

	$[\tau_T = 0]$	$[\tau_T = -0.008]$
$\mathbb{E}(\hat{U})$	0.5858	0.5161
Δ	—	13.50%

Notes: This table reports the welfare costs of temperature shocks. Welfare costs are defined as the percentage increase $\Delta > 0$ in time-zero utility bundle units that the household should receive in order to be indifferent between living in an economy with full risk exposure (i.e. $\sigma_T, \sigma_a, \sigma_g > 0$) and an economy without temperature effects. Temperature effects are eliminated by imposing $\tau_T = 0$.

benchmark calibration, welfare costs amount to 13.50%. According to our specification of the utility bundle, this implies that the time-zero utility consumption units of an agent living in an economy with temperature risk needs to be increased by 13.50% to give the agent the same utility as in an economy without temperature risk.

Government intervention. Given that temperature shocks produce sizable welfare costs, the question of how the government should respond to temperature risk in order to offset these costs can arise. One possibility for the government is to subsidise capital investments of final goods firms in order to promote higher economic growth. Note that one can interpret this as a form of adaption. Another possibility and another form of adaption we consider is a subsidy to R&D investment (one can think of this subsidy as particularly targeted towards the invention of environment-friendly technologies). Finally, the government can levy a lump-sum tax on households to alleviate welfare costs. This tax provides welfare benefits due to the preference for early resolution of uncertainty by households. Hence, levying such a tax discourages consumption and encourages investments due to the substitution motive of households. Due to the positive long-run growth effect of increasing investments, welfare of households increases.

As found in Section 3, in the data, a positive temperature shock reduces growth in R&D expenditure. Our model further suggests that this adverse effect also translates into lower growth of capital investment and output. Higher investment subsidies make investments more profitable by increasing opportunity costs of consumption, such that households postpone consumption now to invest in order to stimulate consumption later. Hence, higher capital investment subsidies lead to higher capital investment and higher R&D expenditure compared to the benchmark. This way, the government can offset the negative effects of temperature shocks on R&D and increase overall welfare of households.

Along these lines, we calculate the required rate of investment subsidies such that welfare costs of temperature risk are zero. The welfare costs are then calculated by comparing the welfare in the economy without temperature risk and without investment subsidies to the welfare in the economy with temperature risk and a positive subsidy rate on investment. We find that the government should subsidise capital investments with a rate of 1.02% of total government expenditure to offset the welfare costs of temperature risk. The simulated moments for the economy with $\tau_i = 0.0102$ are reported in Table C.1 in Appendix C. Welfare gains produced by investment subsidies are followed by a small increase in consumption growth (+12bps). Due to the stimulation of investments into capital, the investment to output ratio (I^*/Y) increases from 14.21% to 14.36% in the (stochastic) steady state.

A subsidy to R&D expenditure works in a similar manner. This is the most effective subsidy, as the amount of R&D expenditure (as a fraction of output) is much lower than of capital investment. Hence, the same absolute amount of government subsidies induces larger effects. Moreover, R&D subsidies directly provide incentives to create more innovations and thus economic growth, which positively affects welfare. Therefore, the subsidy needed to compensate for the welfare costs of global temperature only needs to be 0.52% of total government spending (i.e. $\tau_s = 0.052$). In terms of the simulated moments, the results are very similar to those of the capital investment subsidy.

Finally, a lump-sum tax discourages households to consume. Due to the household owning all firms in the economy, this translates into firms investing more via the effect through the stochastic discount factor of the household. Therefore, we find that the government can fully offset the welfare costs of temperature risk by levying a lump-sum tax on households that finances around 0.64% of total government expenditure (i.e. $\tau_c = -0.00642$). The simulated moments for the economy with $\tau_c = -0.00642$ are also reported in Table C.1 in Appendix C. The simulated moments are again very similar to the other two government intervention cases.

7 Further Inspection of the Mechanism

In this section, we perturb our benchmark model in order to study whether the effects of a global temperature shock on R&D dynamics change in the presence of (i) a different tax regime, (ii) an economy where final output depends less on patents, (iii) a different assumption regarding how temperature shocks affect the depreciation rate of patents, (iv) technology shocks affecting labour productivity and not patent obsolescence, and (v) different values for the household's elasticity of intertemporal substitution. For the sake of brevity, results from these analyses are reported in Appendix C. The main economic intuitions are addressed in what follows.

Different tax regime. Until this point, we have assumed that the government is committed to comply with a zero-deficit rule. To assess the robustness of our results to different tax regimes, we now allow the government to run fiscal deficits, as described by the equations in Appendix C.2. By issuing debt, the government may stabilise economic fluctuations as it is able to employ tax smoothing policies. During recessions, it can increase government debt to allow for lower labour taxes while debt can be reduced during economic expansions by raising taxes. It is therefore straightforward to test whether these government policies are able to reduce the impact of temperature fluctuations on the business cycle and welfare. Simulated moments, welfare costs, and expected growth losses for the new tax regime are reported in Tables C.2, C.3, and C.4, respectively. The results under the new tax regime are basically identical to the case where the government was restricted by a zero-deficit rule. The government subsidy and tax rates required to set off welfare costs of temperature risk are also equal or only slightly different (i.e. $\tau_i = 0.01050$, $\tau_s = 0.00520$, and $\tau_c = -0.00642$). Hence, the quantitative implications of our model do not depend on the assumptions about the tax regime employed by the government.[22]

Decreasing role of R&D. In our framework, we assume that temperature shocks affect the accumulation of patents with the latter being the main driver of economic growth. This raises the question of how sensitive our results are to the importance of R&D in the economy. Strictly speaking, does temperature risk still matter if the role of R&D for economic growth decreases? We test for this by lowering the share of intermediate goods (patents) ξ in the production function of final goods firms from our benchmark value of 0.5652 to a value of 0.3. Due to the balanced growth path restriction, we also need to increase the monopoly markup, i.e. set the parameter ν to 1/2.5167, in this case. The lower ξ, the smaller is the contribution of R&D to economic growth in the model, since the accumulation of patents becomes relatively less important compared to labour and the accumulation of capital.

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[22] Besides the employment-oriented tax rule according to Equation (C.3), we have also tested other rules focusing on deviations of output, consumption, or firm profits. Implications for welfare and business cycles remain unchanged.

In Appendix C.3, we report simulated moments (Table C.5), welfare costs of temperature risk (Table C.6), and expected growth losses (Table C.7). Our main results are left unchanged. Temperature risk still produces an additional equity risk premium of 18bps and generates substantial welfare costs of 11.77%. Expected growth losses are also reduced but only to a small extent. The main differences are that the required investment subsidy rate (lump-sum tax rate) to offset welfare costs by temperature risk is higher compared to the benchmark economy and amounts to 1.999% (1.427%) of government expenditure. The R&D expenditure subsidy rate needed to compensate the welfare costs of temperature risk slightly decreases to 0.595%. As described above, a higher capital investment subsidy rate leads to both an increase in capital investment and R&D investment. However, due to the larger share of capital in the production of aggregate output, the spillover effects to R&D investments are lower compared to the benchmark. Therefore, a larger subsidy rate on capital investment is required to offset the welfare costs of temperature risk. Similarly, the R&D subsidy needed is slightly lower since R&D expenditure is lower in absolute terms due to the lower importance (share) of intermediate goods. Hence, R&D subsidy changes induce a larger effect since total R&D expenditure increases more in relative terms.[23]

Different temperature risk. In the benchmark model, unexpected temperature shocks induce a decrease in R&D expenditure and thus lower economic growth due to their impact on the depreciation rate of patents. In this section, we analyse a model specification, for which all the results are reported in Appendix C.4, Tables C.8, C.9, and C.10, in order to investigate if the model is robust with respect to the concrete way in which temperature risk affects the macro economy. To this end, we specify the process θ_t as follows:

$$\theta_t = \tau_T (T_t - \mu_T). \tag{46}$$

With this specification, it is not unexpected temperature shocks that affect the patent depreciation rate but instead temperature deviations from the long-run mean. Due to the lower persistence in temperature compared to the calibrated persistence of patent depreciation shocks

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[23] Note that the parameter τ_T is set to the same value as in the benchmark calibration and that this generates also a slightly smaller impulse response of R&D expenditure growth to a temperature shock (-0.59pp instead of -0.62pp). To generate the same impulse response as in the benchmark, one would have to set τ_T to a slightly higher value, i.e. $\tau_T - 0.008451$. This would generate slightly higher welfare costs and subsidy/tax rates as well.

in Equation (29), the quantitative effects are smaller. Hence, welfare costs of temperature risk amount to only 5.09%, the capital investment subsidy rate needed to compensate for this welfare loss is just equal to 0.405% of government expenditure, the lump-sum tax rate needed to compensate for the welfare loss is also lower and just equal to -0.249%, and the R&D subsidy is not as high as in the benchmark and equal to 0.199% of government expenditure. However, this way of modelling temperature risk qualitatively provides very similar results. Hence, our main results are robust with respect to the way that temperature risk affects the macro economy.[24]

Different temperature risk 2. One of the potential economic channels for our empirical results discussed in Section 3.3 is that higher temperature leads to lower labour productivity that, consequently, dampens R&D expenditure growth. Additionally, Donadelli, Jüppner, Riedel, and Schlag (2017) incorporate temperature risk through an additional small persistent component in exogenous labour productivity. In this section, we incorporate temperature risk into our model in a similar vein, i.e. we impose that positive temperature shocks harm the exogenous component of labour productivity. Specifically, we specify the processes θ_t and a_t as follows:

$$\theta_t = 0, \tag{47}$$

$$a_t = \rho_a \cdot a_{t-1} + x_t^z + \varepsilon_{a,t}, \tag{48}$$

$$x_t^z = \rho_x^z \cdot x_{t-1}^z + \tau_T \varepsilon_{T,t}. \tag{49}$$

These three equations are used instead of Equations (29) and (15) of the benchmark model. Following Donadelli, Jüppner, Riedel, and Schlag (2017), we use $\rho_x^z = 0.85$ in the calibration. The results are reported in Appendix C.5, Tables C.11, C.12, and C.13.

In this case, welfare costs are much lower and amount to only 3.64% of lifetime utility. Moreover, the capital investment subsidy only needs to be 0.290% of total government spending, the R&D expenditure subsidy only has to amount to 0.142% of total government spending, and the lump-sum tax levied on households only has to finance 0.177% of the total government budget (i.e. $\tau_c = -0.00177$) to fully offset these welfare costs.[25]

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[24] Note again that the parameter τ_T is set to the same value as in the benchmark calibration and that this generates also a smaller impulse response of R&D expenditure growth to a temperature shock (-0.46pp instead of -0.62pp). To generate the same impulse response as in the benchmark, one would have to set τ_T to a higher value, i.e. $\tau_T - 0.010667$, implying higher welfare costs and subsidy/tax rates.

[25] The parameter τ_T is set to the same value as in the benchmark calibration again with the usual implication that the impulse response of R&D expenditure growth to a temperature shock is dampened

The role of the elasticity of intertemporal substitution. A crucial parameter in our model is the elasticity of intertemporal substitution (EIS). First, it is important to set this elasticity above 1 to produce a high equity premium, reasonable equity return volatility, and low risk-free rate. Second, this parameter has a strong influence on the size of the welfare costs induced by global temperature risk and, consequently, on the size of the subsidies needed to fully compensate for these costs. Moreover, there is no consensus on the empirical value for the EIS in the literature since it is hard to quantify this value. Some studies find values (significantly or slightly) below 1 (see, e.g., Hall, 1988; Vissing-Jørgensen, 2002), while others find support for values above 1 (see, e.g., Brown and Kim, 2014; Sönksen, 2017). The meta-analysis by Havránek, Horváth, Irsova, and Rusnák (2015) demonstrates that there is also a lot of cross-country heterogeneity, and they suggest that the EIS tends to increase with stock market participation (in line with Vissing-Jørgensen, 2002).

Therefore, Table C.14 reports the most important macro and asset pricing moments, alongside the welfare costs induced by global temperature risk and the corresponding subsidy or tax rates for the benchmark calibration featuring an EIS of $\psi = 1.85$ and five other calibrations featuring values for the EIS of 2, 1.5, 1.25, 0.75, and 0.5.

The following observations can be made from this exercise. First, the average consumption growth rate declines with decreasing EIS values. Moreover, the correlation between R&D expenditure growth and global temperature, as well as consumption growth volatility increase with decreasing EIS values. The correlation even turns slightly positive for EIS values sufficiently below 1. Due to higher substitution motives with higher EIS values, positive temperature shocks lead to larger decreases in R&D expenditure growth when the EIS is larger, explaining the dynamics of this correlation across the different EIS values. Second, asset pricing moments deteriorate when the EIS decreases. This is not surprising, due to the fact that our model gives rise to endogenous long-run risk (from the endogenous growth mechanism and also global temperature risk), as in Kung and Schmid (2015).[26] Third, welfare costs increase with the EIS value since global temperature risk constitutes an additional long-run risk factor which entails a higher positive market price of risk for higher EIS values. Fourth, the subsidy rates increase in the EIS alongside the welfare costs, but this is true only in the range from 1.5 to 0.5. In the range from

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(-0.18pp instead of -0.62pp). To generate the same impulse response as in the benchmark, one would have to set τ_T to $\tau_T - 0.0280595$, implying significantly higher welfare costs and subsidy/tax rates.

[26] As is well established in the literature (see, e.g., Bansal and Yaron, 2004), long-run risks are only able to contribute to the solution of the equity premium puzzle when the EIS is sufficiently above 1.

1.5 to 2, this monotonicity does not hold. With such large EIS values, the substitution motive becomes very strong (relative to the wealth effect). The firms then significantly increase their investment contributions in response to an increase in any of the three types of subsidies and taxes. We suspect that this increase in investments is so high that the higher welfare costs are compensated for at lower subsidy and tax rate values already (relative to lower EIS values).

8 Concluding Remarks

We provide novel empirical evidence suggesting that a global temperature shock has adverse effects on aggregate expenditure in R&D. We account for this evidence by augmenting a stochastic endogenous growth model with global temperature risk. As in the data, temperature risk undermines both innovation and investment in physical capital. This results in sizable welfare costs that amount to 13.50% of lifetime utility. Such costs can be offset by subsidizing aggregate capital investment with around 1.02% of total government spending, by subsidizing aggregate R&D expenditure with roughly 0.52% of total government spending, or by levying a lump-sum tax on households that finances around 0.64% of total government spending. Therefore, subsidizing R&D expenditure seems to be the smartest choice for the government.

This paper is a first attempt to account for climate change-related phenomena in a stochastic endogenous growth setting. Of course, it can be fruitfully extended under several dimensions. First, it is net of many forms of adaptation such as factor reallocation, transfers, defensive investments, and price changes. Second, it focuses only on temperature as climate change-related shocks. However, there is evidence suggesting that other climate-change related phenomena affect economic activity (e.g., precipitation, hurricanes' frequency, etc.). Third, growth is sustained by homogeneous innovations by entrants only. Coupling temperature risk and heterogeneous innovations could be worth developing. We leave these model extensions for future research.

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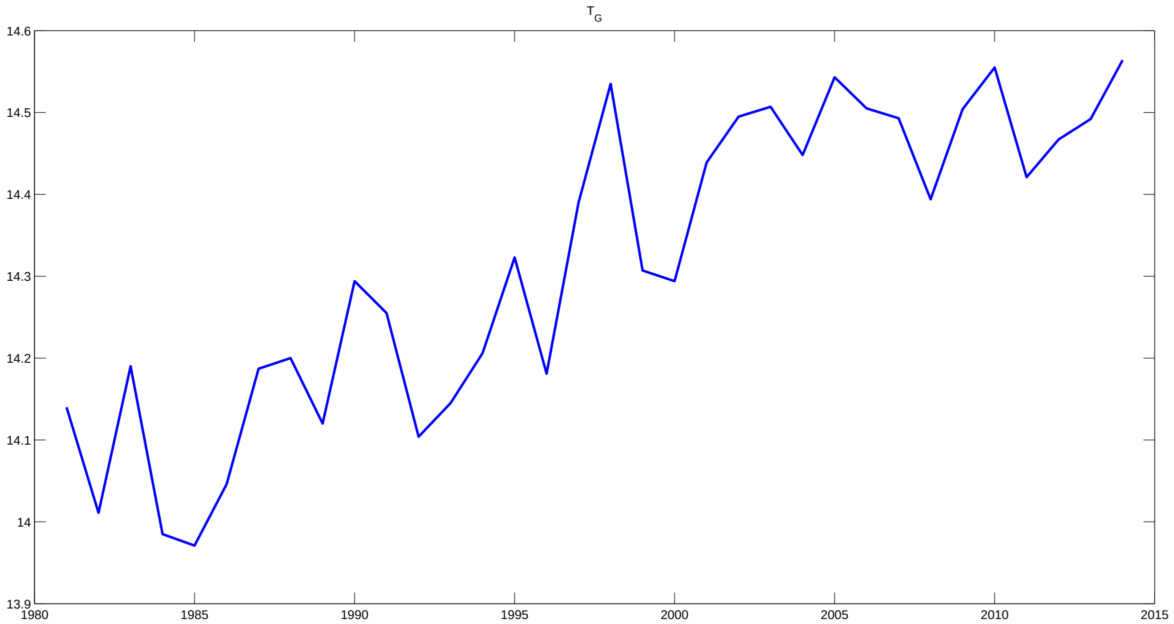
A Data

Macro quantities. Annual growth rates of consumption (*final consumption expenditure of households*), output (*gross domestic product – expenditure approach*), and investment (*gross fixed capital formation*) for the G7 economies have been retrieved from the OECD National Accounts Statistics. Data on the gross domestic expenditure on R&D (GERD) and on the business enterprise expenditure on R&D (BERD) for the G7 economies and OECD group are from the OECD Main Science and Technology Indicators Dataset. Data on the share of government consumption in GDP are taken from the Penn World Table (PWT), version 8.0. All macroeconomic data are annual and run from 1975 to 2014 except for BERD and GERD data that are available for the period 1981–2014.

Asset prices. The equity market return for the G7 is obtained from the G7 (Market) Total Return Index provided by Datastream Global Equity Indices (DGEI). As the proxy for the risk-free rate we use the G7 cross-country short-term interest rates average. Short-term interest rates are from the OECD Monthly Financial Statistics. Nominal rates are converted to real rates by using the "G7 Consumer Price Index (CPI) - all items", which is obtained from the OECD. Data are annual and run from 1975 to 2014.

Temperature. Data on global temperature (expressed in degrees Celsius) have been retrieved from the Climate Research Unit (University of East Anglia), i.e. from `https://crudata.uea.ac.uk/cru/data/temperature/`. Employed temperature data are annual and span the period from 1975 to 2014. Country-level temperatures (expressed in degrees Celsius) are obtained from the Climate Change Knowledge Portal (CCKP). Annual data are averages of monthly observations and span the period from 1981 to 2014.

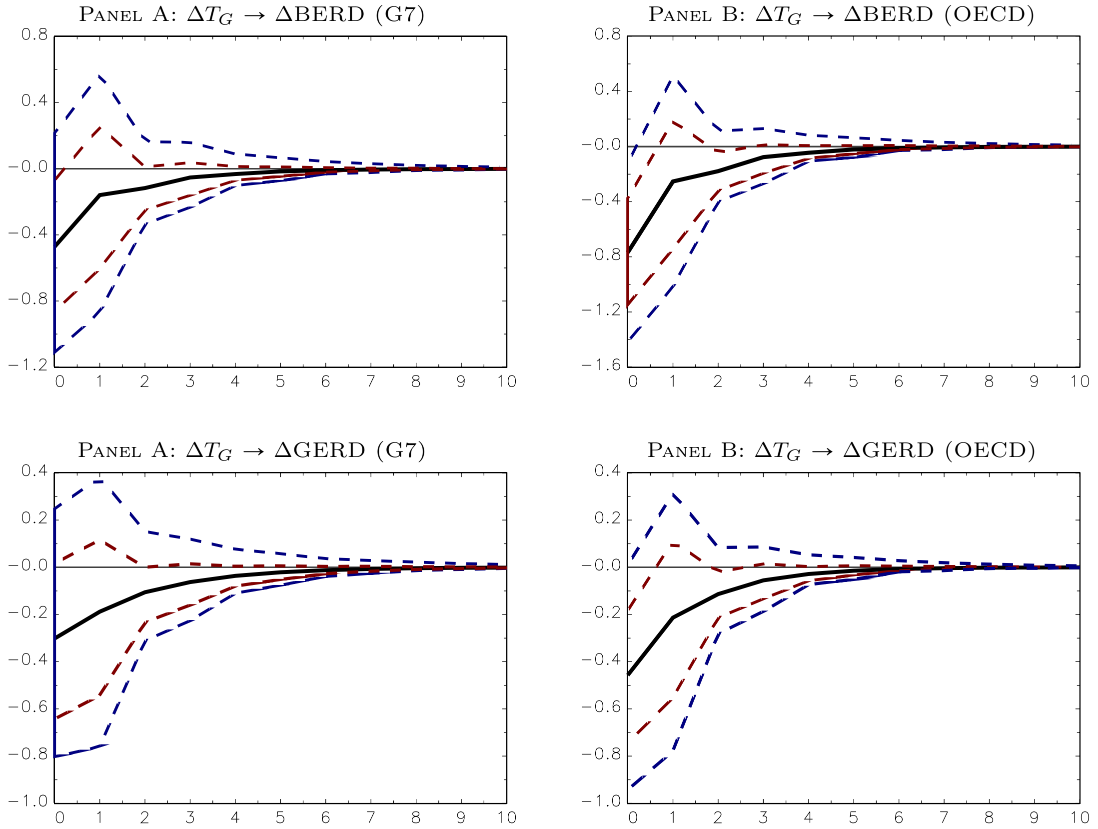
Figure A.1: Global Temperature Series 1981–2014



Notes: This figure depicts the observed global temperature series for the period 1981–2014. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit.

B Additional Empirical Results

Figure B.1: Impulse Response of R&D Expenditure Growth to ΔT_G



Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a shock in the change in global temperature ΔT_G from a bivariate VAR(1) where global temperature growth is ordered first. The VAR(1) model is therefore given by

$$Z_t = C + AZ_{t-1} + \nu_t, \qquad Z_t = [\Delta T_{G,t}, \Delta BERD_t], \qquad \mathbb{E}(\nu_t \nu_t') = V,$$

similar to the VAR(1) model given in Equation (1). Solid black lines: estimated impulse responses. Dashed blue lines: 90% bootstrapped confidence bands. Dashed red lines: 68% bootstrapped confidence bands. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Data are annual and span the period from 1981 to 2014.

Table B.1: Effects of Global Temperature Changes on R&D Expenditure

Panel A: BERD			
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
ΔT_G	-5.571*** (0.001)	-8.558*** (0.009)	-8.566*** (0.010)

Panel B: GERD			
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
ΔT_G	-2.958** (0.034)	-4.060* (0.075)	-4.658** (0.034)

Notes: Panels A and B report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, and the change in global temperature ΔT_G, according to Equation (4). The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Table B.2: Effects of Global and Country-specific Temperature on R&D Expenditure (Arellano-Bond Estimator)

Panel A: $\Delta BERD$ vs. $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-3.481	-17.917***	-17.554***
	(0.179)	(0.001)	(0.000)
k = 3yrs	-1.622	-20.940*	-20.131*
	(0.661)	(0.060)	(0.054)
k = 5yrs	-3.140	-24.990**	-25.077**
	(0.362)	(0.034)	(0.015)

Panel B: $\Delta GERD$ vs. $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-1.783	-0.679	-1.399
	(0.282)	(0.834)	(0.643)
k = 3yrs	-0.386	3.528	3.097
	(0.875)	(0.468)	(0.502)
k = 5yrs	-1.672	0.8620	-0.230
	(0.501)	(0.860)	(0.965)

Panel C: $\Delta BERD$ vs. $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-0.080	-0.488	-0.762
	(0.750)	(0.428)	(0.211)
k = 3yrs	-2.044***	-3.671***	-4.314***
	(0.000)	(0.005)	(0.001)
k = 5yrs	-3.122*	-4.790*	-6.283**
	(0.000)	(0.088)	(0.012)

Panel D: $\Delta GERD$ vs. $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-0.059	0.115	-0.006
	(0.817)	(0.777)	(0.986)
k = 3yrs	-0.961**	-0.725	-1.461
	(0.042)	(0.558)	(0.210)
k = 5yrs	-2.017**	0.517	-1.071
	(0.036)	(0.750)	(0.513)

Notes: Panels A and B report the estimated coefficients on the temperature level from an Arellano-Bond dynamic panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of global temperature $\bar{T}_G^k$, according to Equation (1). Panels C and D report the estimated coefficients on the temperature level from an Arellano-Bond dynamic panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of country-specific temperature $\bar{T}_i^k$. The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Table B.3: Effects of Global and Country-specific Temperature on R&D Expenditure (Controlling for the Global Financial Crisis)

Panel A: $\Delta BERD$ vs. $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-3.495*	-10.830***	-8.283**
	(0.055)	(0.002)	(0.021)
k = 3yrs	-2.233	-9.446**	-6.049
	(0.271)	(0.036)	(0.183)
k = 5yrs	-2.581	-9.089**	-6.172
	(0.188)	(0.018)	(0.120)

Panel B: $\Delta GERD$ vs. $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-2.518**	-3.396**	-1.726
	(0.013)	(0.025)	(0.351)
k = 3yrs	-1.951	-2.814*	-0.194
	(0.144)	(0.086)	(0.931)
k = 5yrs	-2.199	-3.497**	-1.045
	(0.117)	(0.041)	(0.647)

Panel C: $\Delta BERD$ vs. $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-0.364	-0.670	-0.142
	(0.211)	(0.230)	(0.817)
k = 3yrs	-1.370	-2.362***	-1.308
	(0.006)	(0.002)	(0.174)
k = 5yrs	-1.466**	-2.722***	-1.817*
	(0.019)	(0.003)	(0.083)

Panel D: $\Delta GERD$ vs. $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k = 1yr	-0.345	-0.376	0.029
	(0.248)	(0.275)	(0.943)
k = 3yrs	-0.796*	-0.995	-0.242
	(0.066)	(0.147)	(0.747)
k = 5yrs	-1.008*	-0.919	-0.195
	(0.053)	(0.201)	(0.806)

Notes: Panels A and B report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, the moving average of global temperature $\bar{T}_G^k$, and a dummy variable which equals one for the years 2008 and 2009 (and zero otherwise), capturing the negative effects of the global financial crisis, according to Equation (5). Panels C and D report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, the moving average of country-specific temperature $\bar{T}_i^k$, and a dummy variable which equals one for the years 2008 and 2009, capturing the negative effects of the global financial crisis. The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Table B.4: Effects of Global and Country-specific Temperature on R&D Expenditure (Controlling for GDP Growth)

Panel A: $\Delta BERD$ vs $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-1.271	-9.414***	-8.302**
	(0.567)	(0.010)	(0.021)
k=3yrs	0.148	-8.426*	-7.199
	(0.950)	(0.064)	(0.110)
k=5yrs	0.292	-7.257*	-6.373*
	(0.904)	(0.064)	(0.099)

Panel B: $\Delta GERD$ vs $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-1.192	-2.301	-1.562
	(0.202)	(0.109)	(0.351)
k=3yrs	-0.424	-1.845	-0.771
	(0.672)	(0.219)	(0.674)
k=5yrs	-0.343	-1.863	-0.858
	(0.745)	(0.238)	(0.651)

Panel C: $\Delta BERD$ vs $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-0.303	-0.647	-0.509
	(0.226)	(0.297)	(0.405)
k=3yrs	-0.724	-1.752**	-1.225
	(0.244)	(0.023)	(0.172)
k=5yrs	-0.549	-1.928**	-1.508
	(0.438)	(0.048)	(0.147)

Panel D: $\Delta GERD$ vs $\bar{T}_i^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-0.297	-0.406	-0.276
	(0.194)	(0.287)	(0.480)
k=3yrs	-0.319	-0.572	-0.208
	(0.307)	(0.368)	(0.762)
k=5yrs	-0.336	-0.303	0.001
	(0.302)	(0.650)	(0.999)

Notes: Panels A and B report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, the moving average of global temperature $\bar{T}_G^k$, and GDP growth, according to Equation (6). Panels C and D report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, the moving average of country-specific temperature $\bar{T}_i^k$, and GDP growth. The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. The growth rates of GDP are from the OECD Annual National Accounts. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Table B.5: Effects of Global and Country-specific Temperature on R&D Expenditure (Controlling for Consumption Growth)

Panel A: $\Delta BERD$ vs $\bar{T}_G^k$			
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-2.252	-10.12***	-9.488**
	(0.345)	(0.006)	(0.010)
k=3yrs	-0.722	-9.049**	-8.587*
	(0.787)	(0.048)	(0.062)
k=5yrs	-0.946	-8.316**	-8.081**
	(0.730)	(0.032)	(0.041)
Panel B: $\Delta GERD$ vs $\bar{T}_G^k$			
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-1.523	-2.729*	-2.405
	(0.237)	(0.089)	(0.188)
k=3yrs	-0.621	-2.173	-1.652
	(0.690)	(0.211)	(0.415)
k=5yrs	-0.685	-2.437	-1.941
	(0.681)	(0.173)	(0.364)
Panel C: $\Delta BERD$ vs $\bar{T}_i^k$			
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-0.261	-0.548	-0.454
	(0.270)	(0.387)	(0.479)
k=3yrs	-1.042*	-2.201***	-1.794*
	(0.067)	(0.007)	(0.071)
k=5yrs	-1.030	-2.401**	-2.128**
	(0.149)	(0.012)	(0.048)
Panel D: $\Delta GERD$ vs $\bar{T}_i^k$			
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-0.273	-0.300	-0.203
	(0.257)	(0.401)	(0.617)
k=3yrs	-0.462	-0.830	-0.563
	(0.203)	(0.196)	(0.456)
k=5yrs	-0.575	-0.635	-0.452
	(0.195)	(0.361)	(0.582)

Notes: Panels A and B report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, the moving average of global temperature $\bar{T}_G^k$, and consumption growth, according to Equation (6). Panels C and D report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value, the moving average of country-specific temperature $\bar{T}_i^k$, and consumption growth. The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. The growth rates of Consumption are from the OECD Annual National Accounts. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Table B.6: Effects of Global and Country-specific Temperature on R&D Expenditure ("Cooler" vs. "Warmer" Countries)

Panel A: $\Delta BERD$ vs. $\bar{T}_G^k$

	Cooler	Warmer
Horizon	(1)	(2)
k = 1yr	-6.776*	-14.979
	(0.067)	(0.153)
k = 3yrs	-3.648	-19.764
	(0.381)	(0.250)
k = 5yrs	-4.713	-18.604
	(0.233)	(0.155)

Panel B: $\Delta GERD$ vs. $\bar{T}_G^k$

	Cooler	Warmer
Horizon	(1)	(2)
k = 1yr	-0.961	-7.773***
	(0.654)	(0.002)
k = 3yrs	0.264	-7.843**
	(0.916)	(0.026)
k = 5yrs	-0.505	-12.063***
	(0.836	(0.001)

Panel C: $\Delta BERD$ vs. $\bar{T}_i^k$

	Cooler	Warmer
Horizon	(1)	(2)
k = 1yr	-0.500	-0.064
	(0.444)	(0.98)
k = 3yrs	-1.956*	-4.040
	(0.064)	(0.136)
k = 5yrs	-2.254*	-6.443**
	(0.062)	(0.024)

Panel D: $\Delta GERD$ vs. $\bar{T}_i^k$

	Cooler	Warmer
Horizon	(1)	(2)
k = 1yr	-0.059	-1.077
	(0.886)	(0.628)
k = 3yrs	-0.670	-2.034
	(0.384)	(0.244)
k = 5yrs	-0.457	-3.877***
	(0.580)	(0.000)

Notes: Panels A and B report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of global temperature $\bar{T}_G^k$, according to Equation (2). Panels C and D report the estimated coefficients on the temperature level from a dynamic fixed effects panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of country-specific temperature $\bar{T}_i^k$. We use data for the OECD+ countries and divide the sample into relatively warmer and relatively cooler countries. The models are estimated on "cooler" countries in column (1), while we use data for "warmer" countries in column (2). The latter group comprises Argentina, Australia, Greece, Israel, Mexico, Portugal, Singapore, Spain, and South Africa. The former group includes all the remaining countries. Robust standard errors are computed by clustering standard errors at the country level. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Table B.7: Effects of Global and Country-specific Temperature on R&D Expenditure (Random-Coefficients Model)

Panel A: $\Delta BERD$ vs $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-3.688**	-11.030***	-8.257*
	(0.018)	(0.006)	(0.063)
k=3yrs	-2.746	-13.460	-4.961
	(0.147)	(0.337)	(0.714)
k=5yrs	-3.482**	-8.781	-4.249
	(0.043)	(0.283)	(0.546)

Panel B: $\Delta GERD$ vs $\bar{T}_G^k$

	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-2.495***	-1.793	-1.206
	(0.008)	(0.330)	(0.565)
k=3yrs	-2.078*	0.744	3.922
	(0.087)	(0.777)	(0.310)
k=5yrs	-2.512**	-0.930	0.724
	(0.015)	(0.712)	(0.847)

Panel C: $\Delta BERD$ vs $\bar{T}_i^k$

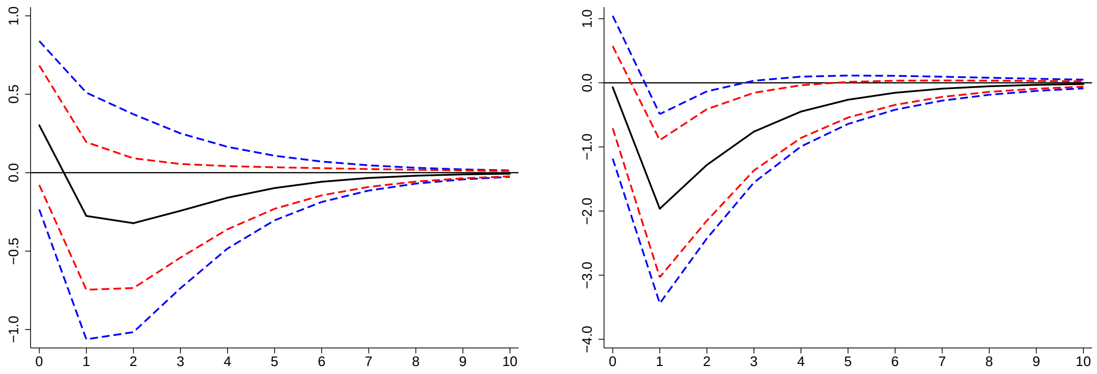
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-0.170	-0.461	-0.142
	(0.720)	(0.508)	(0.803)
k=3yrs	-1.371***	-3.144*	-2.229
	(0.008)	(0.052)	(0.118)
k=5yrs	-1.614**	-3.025**	-2.830*
	(0.030)	(0.042)	(0.063)

Panel D: $\Delta GERD$ vs $\bar{T}_i^k$

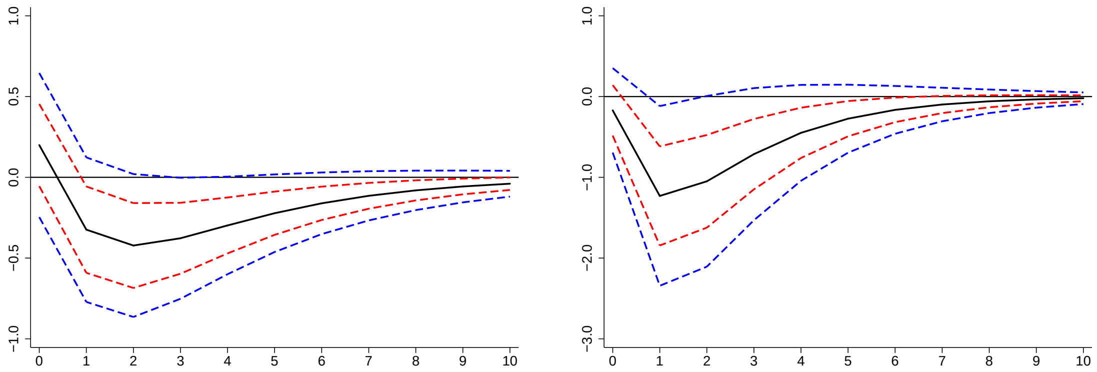
	G7	OECD	OECD+
Horizon	(1)	(2)	(3)
k=1yr	-0.323	-0.251	-0.164
	(0.314)	(0.429)	(0.419)
k=3yrs	-0.837*	-0.768*	-0.403
	(0.055)	(0.071)	(0.409)
k=5yrs	-1.199**	-0.394	-0.385
	(0.048)	(0.644)	(0.720)

Notes: Panels A and B report the estimated coefficients on the temperature level from a random-coefficients panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of global temperature $\bar{T}_G^k$, according to Equation (7). Panels C and D report the estimated coefficients on the temperature level from a random-coefficients panel regression of BERD (GERD) growth rate $\Delta BERD_{i,t}$ ($\Delta GERD_{i,t}$) on its lagged value and the moving average of country-specific temperature $\bar{T}_i^k$. The models are estimated on data for the G7 countries in column (1), while we use data for the full OECD group and all OECD members plus seven additional countries (Argentina, China, Romania, Russia, Singapore, South Africa, and Chinese Taipei) in columns (2) and (3), respectively. Standard errors are calculated using bootstrap estimation. The p-values are reported in parentheses. The growth rates of BERD (GERD) for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Countries' annual average temperatures (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Temperature data are not available for Chinese Taipei. The sample is 1981–2014. ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively.

Figure B.2: Impulse Response of R&D Expenditure Growth to Country-specific Temperature Shocks (Panel VAR)


Panel A: $T_i \rightarrow \Delta BERD(G7)$

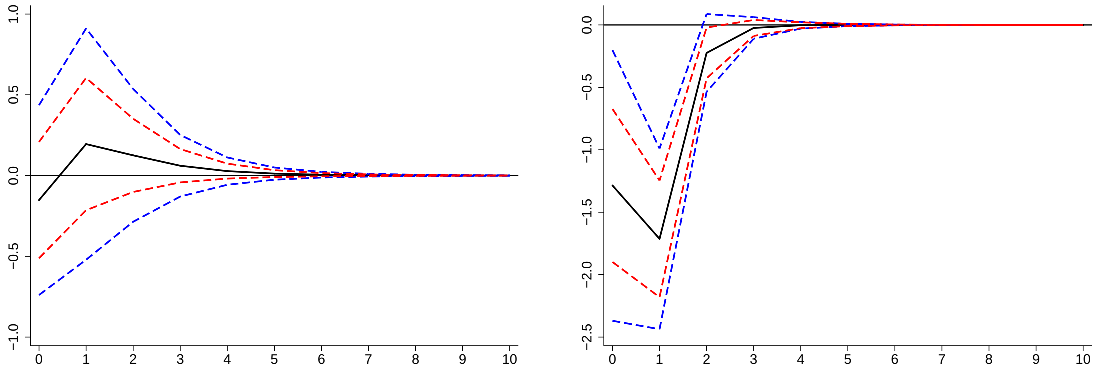
Panel B: $T_i \rightarrow \Delta BERD(OECD)$


Panel A: $T_i \rightarrow \Delta GERD(G7)$

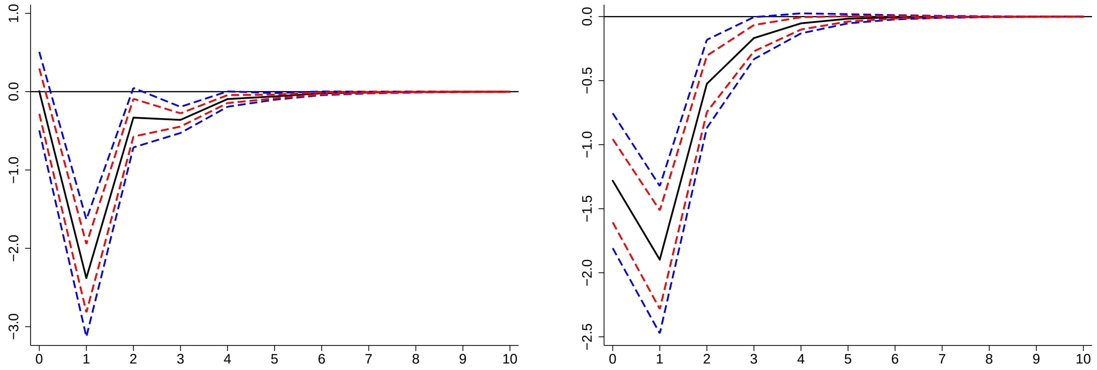
Panel B: $T_i \rightarrow \Delta GERD(OECD)$

Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a country-specific temperature shock. Impulse responses are obtained by estimating a bivariate Panel-VAR(1) according to Equation (3) using the Generalised Method of Moments (GMM) where country-specific temperature is ordered first. The lag order of the dependent variables to be used as instruments is chosen to be four. The Panel-VAR satisfies stability conditions. Solid black lines: estimated impulse responses. Dashed blue lines: 90% confidence bands obtained by Monte Carlo draws. Dashed red lines: 68% confidence bands obtained by Monte Carlo draws. Robust standard errors are computed by clustering standard errors at the country level. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on country-specific temperature (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Data are annual and span the period from 1981 to 2014.

Figure B.3: Impulse Response of R&D Expenditure Growth to a Shock in ΔT_G (Panel VAR)



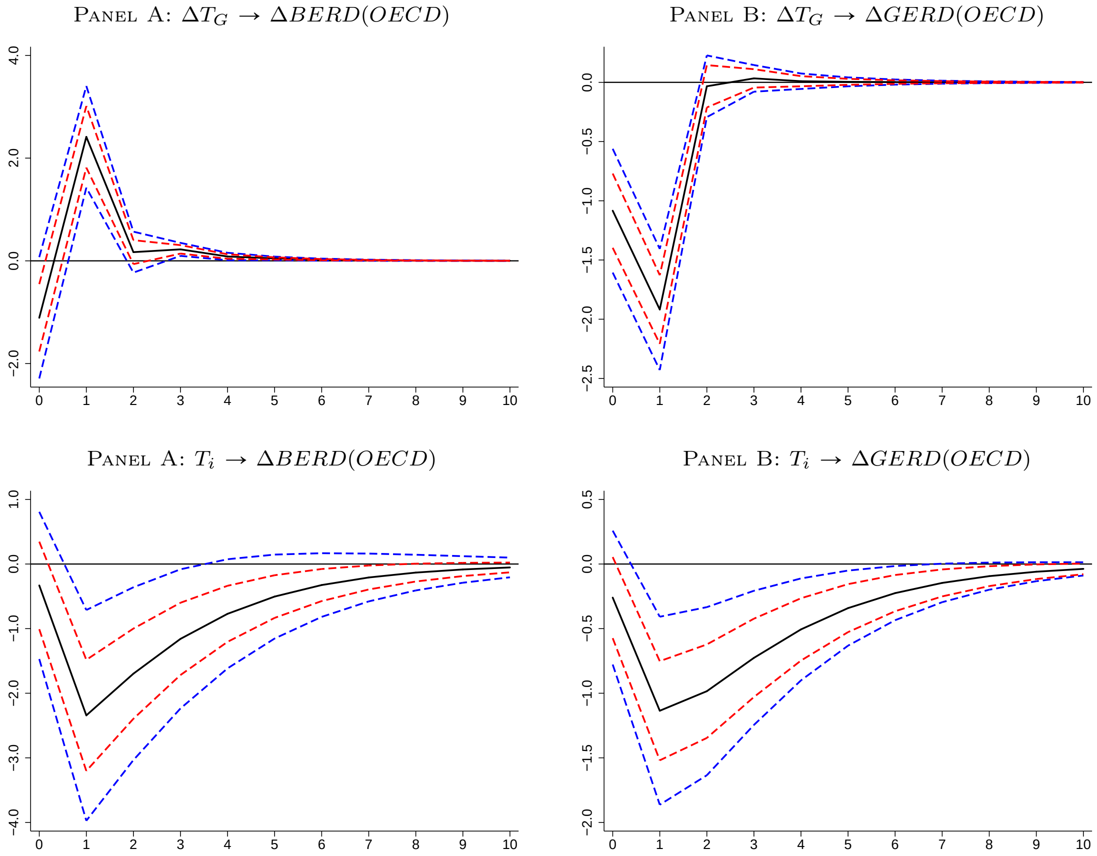
Panel A: $\Delta T_G \rightarrow \Delta BERD(G7)$ Panel B: $\Delta T_G \rightarrow \Delta BERD(OECD)$



Panel A: $\Delta T_G \rightarrow \Delta GERD(G7)$ Panel B: $\Delta T_G \rightarrow \Delta GERD(OECD)$

Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a shock in the first difference of global temperature ΔT_G. Impulse responses are obtained by estimating a bivariate Panel-VAR(1) according to Equation (3) using the Generalised Method of Moments (GMM) where global temperature growth is ordered first. The lag order of the dependent variables to be used as instruments is chosen to be four. The Panel-VAR satisfies stability conditions. Solid black lines: estimated impulse responses. Dashed blue lines: 90% confidence bands obtained by Monte Carlo draws. Dashed red lines: 68% confidence bands obtained by Monte Carlo draws. Robust standard errors are computed by clustering standard errors at the country level. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. Data on global temperature (expressed in degrees Celsius) are from the Climate Research Unit. Data are annual and span the period from 1981 to 2014.

Figure B.4: Impulse Response of R&D Expenditure Growth to Global and Country-specific Temperature Shocks (Panel VAR): Controlling for GDP Growth



Panel A: $\Delta T_G \rightarrow \Delta BERD(OECD)$

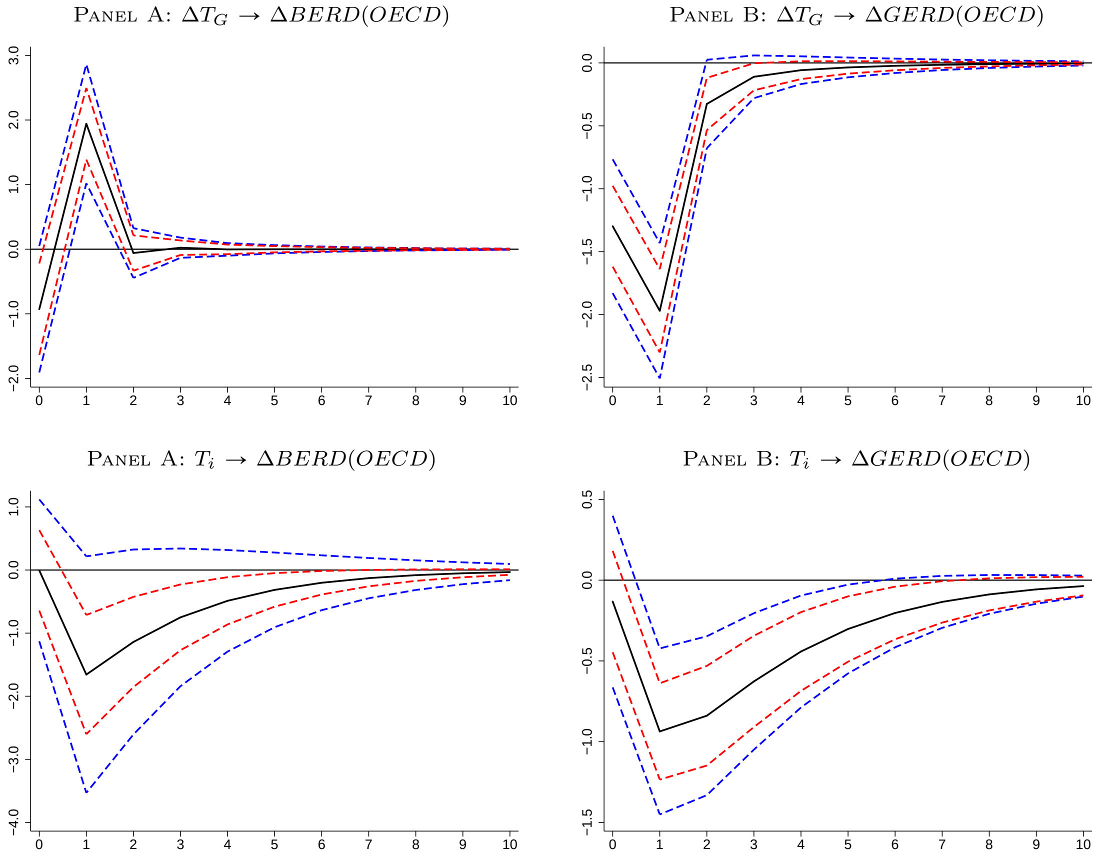
Panel B: $\Delta T_G \rightarrow \Delta GERD(OECD)$

Panel A: $T_i \rightarrow \Delta BERD(OECD)$

Panel B: $T_i \rightarrow \Delta GERD(OECD)$

Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a country-specific temperature shock and a shock in the first difference of global temperature ΔT_G. Impulse responses are obtained by estimating a trivariate Panel-VAR(1) according to Equation (3) adding GDP growth as additional endogenous variable using the Generalised Method of Moments (GMM) where temperature is ordered first and R&D growth is ordered last. The lag order of the dependent variables to be used as instruments is chosen to be four. The Panel-VAR satisfies stability conditions. Solid black lines: estimated impulse responses. Dashed blue lines: 90% confidence bands obtained by Monte Carlo draws. Dashed red lines: 68% confidence bands obtained by Monte Carlo draws. Robust standard errors are computed by clustering standard errors at the country level. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. The growth rates of GDP are from the OECD Annual National Accounts. Data on country-specific temperature (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Data are annual and span the period from 1981 to 2014.

Figure B.5: Impulse Response of R&D Expenditure Growth to Global and Country-specific Temperature Shocks (Panel VAR): Controlling for Consumption Growth


Panel A: $\Delta T_G \rightarrow \Delta BERD(OECD)$

Panel B: $\Delta T_G \rightarrow \Delta GERD(OECD)$

Panel A: $T_i \rightarrow \Delta BERD(OECD)$

Panel B: $T_i \rightarrow \Delta GERD(OECD)$

Notes: This figure presents Cholesky orthogonalised impulse responses of R&D growth to a country-specific temperature shock and a shock in the first difference of global temperature ΔT_G. Impulse responses are obtained by estimating a trivariate Panel-VAR(1) according to Equation (3) adding consumption growth as additional endogenous variable using the Generalised Method of Moments (GMM) where temperature is ordered first and R&D growth is ordered last. The lag order of the dependent variables to be used as instruments is chosen to be four. The Panel-VAR satisfies stability conditions. Solid black lines: estimated impulse responses. Dashed blue lines: 90% confidence bands obtained by Monte Carlo draws. Dashed red lines: 68% confidence bands obtained by Monte Carlo draws. Robust standard errors are computed by clustering standard errors at the country level. The growth rates of BERD and GERD for the G7 and OECD are from the OECD Main Science and Technology Indicators Database. The growth rates of Consumption are from the OECD Annual National Accounts. Data on country-specific temperature (expressed in degrees Celsius) are from the Climate Change Knowledge Portal (CCKP). Data are annual and span the period from 1981 to 2014.

C Additional Quantitative Results

This appendix reports additional quantitative results, based on variations of the benchmark model.

C.1 Government interventions

Table C.1 reports the simulated moments of the economy incorporating capital investment subsidies and consumption transfers, respectively, that offset the welfare costs caused by temperature shocks.

Table C.1: Simulated Moments: Government Interventions

Variable	**Data**	**Benchmark**	$\tau_i = 0.01020$	$\tau_s = 0.00520$	$\tau_c = -0.00642$
		[1]	**[2]**	**[3]**	**[4]**
MACRO QUANTITIES					
$\mathbb{E}(\Delta c^*)$	2.25	**2.25**	2.36	2.37	2.37
$\sigma(\Delta y)$	1.60	**1.60**	1.61	1.60	1.61
$\sigma(\Delta c^*)$	1.20	**1.14**	1.14	1.15	1.14
$\sigma(\Delta c^*)/\sigma(\Delta y)$	0.75	**0.71**	0.71	0.72	0.71
$\sigma(\Delta i^*)/\sigma(\Delta y)$	2.05	**1.05**	1.05	1.05	1.05
$\sigma(\Delta s^*)/\sigma(\Delta y)$	1.92	**1.95**	1.94	1.93	1.94
$\rho(\Delta c^*, \Delta y)$	0.87	**0.65**	0.64	0.65	0.63
$\rho(\Delta c^*, \Delta i^*)$	0.81	**0.66**	0.65	0.65	0.64
$\rho(\Delta i^*, \Delta y)$	0.93	**0.99**	0.99	0.99	0.99
$\rho(\Delta s^*, \Delta y)$	0.59	**0.98**	0.98	0.98	0.98
$\rho(\Delta s^*, T)$	-0.46	**-0.11**	-0.11	-0.11	-0.11
$\partial \Delta s^* / \partial \varepsilon_T$	-0.57	**-0.62**	-0.62	-0.61	-0.62
TEMPERATURE					
$\mathbb{E}(T)$	14.27	**14.27**	14.27	14.27	14.27
$\sigma(T)$	0.23	**0.23**	0.23	0.23	0.23
ASSET PRICES					
$\mathbb{E}(R^f)$	2.38	**2.32**	2.37	2.38	2.38
$\sigma(R^f)$	2.88	**0.20**	0.20	0.20	0.20
$\mathbb{E}[R_{ex}^{LEV}]$	5.72	**1.49**	1.52	1.52	1.52
$\sigma(R_{ex}^{LEV})$	14.72	**4.64**	4.67	4.65	4.67

Notes: This table reports the main moments for the benchmark calibration (specification [1]), the model with a capital investment subsidy rate of 1.02% that offsets welfare costs of temperature risk (specification [2]), the model with a R&D investment subsidy rate of 0.52% that also offsets welfare costs of temperature risk (specification [3]), and the model with a lump-sum tax rate of -0.642% that offsets welfare costs of temperature risk as well (specification [4]). The aggregate market return is levered as in Croce (2014). Models' entries are obtained from repetitions of small-sample simulations (i.e. averages over 3000 simulations of 41 years). $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot, \cdot)$ denote mean, volatility, and correlation, respectively, and $\partial \Delta s^* / \partial \varepsilon_T$ denotes the initial response of R&D expenditure growth to a one standard deviation shock in temperature in percentage points. Means and standard deviations are expressed in percentage points. Data on global temperature and G7 macro-aggregates are from the Climate Research Unit and the OECD, respectively. Data are annual and run from 1975 (or later) to 2014. Additional details on the data are provided in Appendix A.

C.2 Tax smoothing policy

If the government is not committed to a zero-deficit rule, the new government budget constraint becomes:

$$G_t + R_{f,t-1}B_{t-1} = -\tau_c G_t + \tau_{l,t} W_t^u L_t + \tau_\pi N_t \Pi_t + B_t, \tag{C.1}$$

where the government has an additional instrument to finance its public spending. Besides using taxes on labour income, corporate profits, and household's consumption, it can issue public debt B_t and thus run budget deficits. We assume that the debt-output ratio follows the process:

$$\frac{B_t}{Y_t} = \rho_b \frac{B_{t-1}}{Y_{t-1}} + \phi_b \left(\ln(L_{ss}) - \ln(L_t)\right), \tag{C.2}$$

where $\rho_b \in (0, 1)$ captures the delay of debt repayment, $\phi_b \geqslant 0$ is a scale parameter, and L_{ss} is the steady-state level of labour. This implies that the labour tax rate is determined by:

$$\tau_{l,t} = \tau_{l,t}^0 + \frac{Y_t}{W_t^u L_t} \left[\left(\frac{R_{f,t-1}}{Y_t/Y_{t-1}} - \rho_b \right) \frac{B_{t-1}}{Y_{t-1}} + \phi_b \left(\ln(L_t) - \ln(L_{ss})\right) \right], \tag{C.3}$$

where $\tau_{l,t}^0$ is the zero-deficit tax rate as in Equation (38). Following Croce, Nguyen, and Schmid (2014) we use an employment-oriented tax rule and set $\phi_b > 0$. In bad times when labour falls below the steady state level, the government cuts taxes on labour income (i.e. increases debt), whereas in good times (booms), it increases taxes (i.e. reduces debt). Note that the second term on the right-hand side of Equation (C.3) accounts also for the long-lasting effect on taxes caused by debt repayment and that by imposing $\rho_b \in (0, 1)$ we rule out unstable fluctuations of the debt-output ratio. In line with the calibration reported in Croce, Nguyen, and Schmid (2013), we set the intensity of the smoothing policy ϕ_b and the related the inverse of the speed of debt repayment ρ_b to values of 0.025 and $\sqrt[4]{0.975}$, respectively.

Given that the households holds government bonds B_t, the new budget constraint of the representative household becomes:

$$C_t^* + B_t = C_t + \tau_c G_t + B_t = (1 - \tau_{l,t}) W_t^u L_t + R_{f,t-1} B_{t-1} + \tau_c G_t + D_{a,t} - S_t. \tag{C.4}$$

The simulated moments using the just described fiscal rule are reported in Table C.2, the corresponding welfare implications are reported in Table C.3, and the corresponding long-run output growth losses in Table C.4.

Table C.2: SIMULATED MOMENTS (DIFFERENT TAX REGIME)

Variable	**Data**	**Benchmark**	$\tau_T < 0$	$\tau_T = 0$
		[1]	**[2]**	**[3]**
MACRO QUANTITIES				
$\mathbb{E}(\Delta c^*)$	2.25	**2.25**	2.25	2.25
$\sigma(\Delta y)$	1.60	**1.60**	1.47	1.46
$\sigma(\Delta c^*)$	1.20	**1.14**	1.13	1.05
$\sigma(\Delta c^*)/\sigma(\Delta y)$	0.75	**0.71**	0.77	0.72
$\sigma(\Delta i^*)/\sigma(\Delta y)$	2.05	**1.05**	1.07	1.05
$\sigma(\Delta s^*)/\sigma(\Delta y)$	1.92	**1.95**	1.86	1.83
$\rho(\Delta c^*, \Delta y)$	0.87	**0.65**	0.65	0.40
$\rho(\Delta c^*, \Delta i^*)$	0.81	**0.66**	0.65	0.32
$\rho(\Delta i^*, \Delta y)$	0.93	**0.99**	0.99	0.99
$\rho(\Delta s^*, \Delta y)$	0.59	**0.98**	0.98	0.97
$\rho(\Delta s^*, T)$	-0.46	**-0.11**	-0.12	0.00
$\partial \Delta s^* / \partial \varepsilon_T$	-0.57	**-0.62**	-0.57	0.00
TEMPERATURE				
$\mathbb{E}(T)$	14.27	**14.27**	14.27	14.27
$\sigma(T)$	0.23	**0.23**	0.23	0.23
ASSET PRICES				
$\mathbb{E}(R^f)$	2.31	**2.32**	2.35	2.39
$\sigma(R^f)$	2.88	**0.20**	0.19	0.14
$\mathbb{E}[R_{ex}^{LEV}]$	5.72	**1.49**	1.42	1.24
$\sigma(R_{ex}^{LEV})$	14.72	**4.63**	4.42	4.26

Notes: This table reports the main moments for the benchmark calibration (specification [1]), the main moments for the model with the tax-smoothing policy in place and temperature risk, i.e. $\tau_T < 0$ in Equation (29) (specification [2]), and the model with the tax-smoothing policy in place but where temperature does not affect the obsolescence rate of patents (specification [3]), i.e. $\tau_T = 0$ in Equation (29). In specifications [2] and [3], the government is allowed to run a budget deficit according to the equations in Appendix C.2. The aggregate market return is levered as in Croce (2014). Models' entries are obtained from repetitions of small-sample simulations (i.e. averages over 3000 simulations of 41 years). $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot,\cdot)$ denote mean, volatility, and correlation, respectively, and $\partial \Delta s^* / \partial \varepsilon_T$ denotes the initial response of R&D expenditure growth to a one standard deviation shock in temperature in percentage points. Means and standard deviations are expressed in percentage points. Data on global temperature and G7 macro-aggregates are from the Climate Research Unit and the OECD, respectively. Data are annual and run from 1975 (or later) to 2014. Additional details on the data are provided in Appendix A.

Table C.3: WELFARE COSTS OF TEMPERATURE RISK (DIFFERENT TAX REGIME)

	$[\tau_T = 0]$	$[\tau_T = -0.008]$
$\mathbb{E}(\hat{U})$	0.5934	0.5235
Δ	—	13.35%

Notes: This table reports the welfare costs of temperature shocks when the government is allowed to run a budget deficit. Welfare costs are defined as the percentage increase $\Delta > 0$ in time-zero utility bundle units that the household should receive in order to be indifferent between living in an economy with full risk exposure (i.e. $\sigma_T, \sigma_a, \sigma_g > 0$) and an economy without temperature effects. Temperature effects are eliminated by imposing $\tau_T = 0$.

Table C.4: Long-run Effects of Temperature Shocks (Different Tax Regime)

Panel A: Single Transitory Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_T	−0.14	−0.48	−0.78	−1.16	−1.57
2 std. dev. σ_T	−0.28	−0.95	−1.55	−2.31	−3.14
Panel B: Multiple Transitory Shocks — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1981–2014	1981–2030			
obs. shocks 1981–2014	−0.90	−2.52			
Panel C: Permanent Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	16Y				
0.379°C	−9.93				

Notes: Panel A of this table reports the cumulative change in output growth over 1, 5, 10, 20, and 50 years in percentage points after a temporary temperature shock for the specification where the government is allowed to run a budget deficit. The cumulative growth in an economy without such a shock is compared to that in an economy with shocks to temperature (i.e. with $\varepsilon_t > 0$). Specifically, we report $(\sum_{j=1}^{N} \Delta y_{t+j}) - N \cdot \Delta y^*$ where Δy_{t+j} is the log growth rate of total output, and Δy^* is the steady state growth rate in the economy without a shock (i.e. with $\varepsilon_t = 0$). For example, the entry −0.48 for a horizon of 5 years in the first row means that cumulative output growth over these 5 years has been 0.48 percentage points lower than it would have been without the temperature shock. The amount of lost output growth is reported for temperature shocks amounting to one and two standard deviations, i.e. to 0.12°C and 0.24°C, respectively. Panel B reports the cumulative change in output growth if the observed shocks to global temperature (both positive and negative shocks) in the period 1981–2014, backed out from the data by using the definition $\varepsilon_{T,t} = T_{G,t} - T_{G,t-1}$, are used in the model simulation. For the entry under the heading "1981–2030", it is assumed that there are no shocks after 2014. Therefore, the additional cumulative change in output growth is due to the persistent effects of temperature shocks on the patent obsolescence rate that still affect the model years 2014–2030. Panel C reports the cumulative change in output growth for a period of 16 years after a permanent global temperature shock, translating into a permanent increase of the patent obsolescence rate (i.e. we assume $\rho_\theta = 1$). The observed global temperature change, used as the permanent shock, is calculated by subtracting the average global temperature for the first 10 years of the data (1981–1990) from the average global temperature of the last 10 years of data (2005–2014). This calculation gives rise to a change in global temperature of 0.379°C.

C.3 Decreasing role of R&D

Table C.5: Simulated Moments (Decreasing Role of R&D)

Variable	**Data**	**Benchmark**	$\xi = 0.3$ **and** $\tau_T < 0$	$\xi = 0.3$ **and** $\tau_T = 0$
		[1]	**[2]**	**[3]**
MACRO QUANTITIES				
$\mathbb{E}(\Delta c^*)$	2.25	**2.25**	2.08	2.07
$\sigma(\Delta y)$	1.60	**1.60**	1.47	1.45
$\sigma(\Delta c^*)$	1.20	**1.14**	1.08	1.03
$\sigma(\Delta c^*)/\sigma(\Delta y)$	0.75	**0.71**	0.73	0.71
$\sigma(\Delta i^*)/\sigma(\Delta y)$	2.05	**1.05**	1.09	1.07
$\sigma(\Delta s^*)/\sigma(\Delta y)$	1.92	**1.95**	2.12	2.11
$\rho(\Delta c^*, \Delta y)$	0.87	**0.65**	0.87	0.91
$\rho(\Delta c^*, \Delta i^*)$	0.81	**0.66**	0.84	0.92
$\rho(\Delta i^*, \Delta y)$	0.93	**0.99**	0.99	1.00
$\rho(\Delta s^*, \Delta y)$	0.59	**0.98**	0.97	0.98
$\rho(\Delta s^*, T)$	-0.46	**-0.11**	-0.11	0.00
$\partial \Delta s^* / \partial \varepsilon_T$	-0.57	**-0.62**	-0.59	0.00
TEMPERATURE				
$\mathbb{E}(T)$	14.27	**14.27**	14.27	14.27
$\sigma(T)$	0.23	**0.23**	0.23	0.23
ASSET PRICES				
$\mathbb{E}(R^f)$	2.31	**2.32**	2.31	2.34
$\sigma(R^f)$	2.88	**0.20**	0.21	0.17
$\mathbb{E}[R_{ex}^{LEV}]$	5.72	**1.49**	1.26	1.10
$\sigma(R_{ex}^{LEV})$	14.72	**4.63**	4.33	4.15

Notes: This table reports the main moments for the benchmark calibration (specification [1]) and two other model specifications. In models [2] and [3], intermediate goods enter the production function with a smaller share compared to the benchmark economy (and a higher monopoly markup is required due to the balanced growth restriction), i.e. $\xi = 0.3$ (and $\nu = 1/2.5167$) vs. $\xi = 0.57$ (and $\nu = 1/1.5$). Note that also and the productivity parameter χ changes slightly as well as the labour elasticity parameter τ in order to keep the deterministic steady state growth rate the same (i.e. equal to 0.019) and the deterministic steady state labour share the same (i.e. equal to 1/3) in the specifications [2] and [3]. In specification [1] and [2], temperature affects the obsolescence rate of patents, i.e. $\tau_T < 0$ in Equation (29) while in specification [3], temperature effects are offset, i.e, $\tau_T = 0$. The aggregate market return is levered as in Croce (2014). Models' entries are obtained from repetitions of small-sample simulations (i.e. averages over 3000 simulations of 41 years). $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot,\cdot)$ denote mean, volatility, and correlation, respectively, and $\partial \Delta s^* / \partial \varepsilon_T$ denotes the initial response of R&D expenditure growth to a one standard deviation shock in temperature in percentage points. Means and standard deviations are expressed in percentage points. Data on global temperature and G7 macro-aggregates are from the Climate Research Unit and the OECD, respectively. Data are annual and run from 1975 (or later) to 2014. Additional details on the data are provided in Appendix A.

Table C.6: Welfare Costs of Temperature Risk (Decreasing Role of R&D)

	$[\tau_T = 0]$	$[\tau_T = -0.008]$
$\mathbb{E}(\hat{U})$	2.2368	2.0011
Δ	—	11.77%

Notes: This table reports the welfare costs of temperature shocks for the specification where intermediate goods enter the production function with a smaller share compared to the benchmark economy, i.e. $\xi = 0.3$. Due to the balanced growth restriction, we also need to impose a higher monopoly markup compared to the benchmark economy, i.e. $\nu = 1/2.5167$. Welfare costs are defined as the percentage increase $\Delta > 0$ in time-zero utility bundle units that the household should receive in order to be indifferent between living in an economy with full risk exposure (i.e. $\sigma_T, \sigma_a, \sigma_g > 0$) and an economy without temperature effects. Temperature effects are eliminated by imposing $\tau_T = 0$.

Table C.7: Long-run Effects of Temperature Shocks (Decreasing Role of R&D)

Panel A: Single Transitory Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_T	−0.11	−0.44	−0.75	−1.13	−1.55
2 std. dev. σ_T	−0.22	−0.89	−1.50	−2.27	−3.09
Panel B: Multiple Transitory Shocks — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1981–2014	1981–2030			
obs. shocks 1981–2014	−0.99	−2.62			
Panel C: Permanent Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	16Y				
0.379°C	−7.96				

Notes: Panel A of this table reports the cumulative change in output growth over 1, 5, 10, 20, and 50 years in percentage points after a temporary temperature shock for the specification where intermediate goods enter the production function with a smaller share compared to the benchmark economy, i.e. $\xi = 0.3$. Due to the balanced growth restriction, we also need to impose a higher monopoly markup compared to the benchmark economy, i.e. $\nu = 1/2.5167$. The cumulative growth in an economy without such a shock is compared to that in an economy with shocks to temperature (i.e. with $\varepsilon_t > 0$). Specifically, we report $(\sum_{j=1}^{N} \Delta y_{t+j}) - N \cdot \Delta y^*$ where Δy_{t+j} is the log growth rate of total output, and Δy^* is the steady state growth rate in the economy without a shock (i.e. with $\varepsilon_t = 0$). For example, the entry −0.44 for a horizon of 5 years in the first row means that cumulative output growth over these 5 years has been 0.44 percentage points lower than it would have been without the temperature shock. The amount of lost output growth is reported for temperature shocks amounting to one and two standard deviations, i.e. to 0.12°C and 0.24°C, respectively. Panel B reports the cumulative change in output growth if the observed shocks to global temperature (both positive and negative shocks) in the period 1981–2014, backed out from the data by using the definition $\varepsilon_{T,t} = T_{G,t} - T_{G,t-1}$, are used in the model simulation. For the entry under the heading "1981–2030", it is assumed that there are no shocks after 2014. Therefore, the additional cumulative change in output growth is due to the persistent effects of temperature shocks on the patent obsolescence rate that still affect the model years 2014–2030. Panel C reports the cumulative change in output growth for a period of 16 years after a permanent global temperature shock, translating into a permanent increase of the patent obsolescence rate (i.e. we assume $\rho_\theta = 1$). The observed global temperature change, used as the permanent shock, is calculated by subtracting the average global temperature for the first 10 years of the data (1981–1990) from the average global temperature of the last 10 years of data (2005–2014). This calculation gives rise to a change in global temperature of 0.379°C.

C.4 Different temperature risk

Table C.8: Simulated Moments (Different Temperature Risk)

Variable	Data	Benchmark	$\tau_T < 0$	$\tau_T = 0$
		[1]	**[2]**	**[3]**
MACRO QUANTITIES				
$\mathbb{E}(\Delta c^{*})$	2.25	**2.25**	2.23	2.25
$\sigma(\Delta y)$	1.60	**1.60**	1.62	1.59
$\sigma(\Delta c^{*})$	1.20	**1.14**	1.11	1.07
$\sigma(\Delta c^{*})/\sigma(\Delta y)$	0.75	**0.71**	0.70	0.68
$\sigma(\Delta i^{*})/\sigma(\Delta y)$	2.05	**1.05**	1.03	1.03
$\sigma(\Delta s^{*})/\sigma(\Delta y)$	1.92	**1.95**	1.94	1.92
$\rho(\Delta c^{*}, \Delta y)$	0.87	**0.65**	0.67	0.70
$\rho(\Delta c^{*}, \Delta i^{*})$	0.81	**0.66**	0.71	0.76
$\rho(\Delta i^{*}, \Delta y)$	0.93	**0.99**	0.99	0.99
$\rho(\Delta s^{*}, \Delta y)$	0.59	**0.98**	0.98	0.99
$\rho(\Delta s^{*}, T)$	-0.46	**-0.11**	-0.07	0.00
$\partial \Delta s^{*}/\partial \varepsilon_T$	-0.57	**-0.62**	-0.46	0.00
TEMPERATURE				
$\mathbb{E}(T)$	14.27	**14.27**	14.27	14.27
$\sigma(T)$	0.23	**0.23**	0.23	0.23
ASSET PRICES				
$\mathbb{E}(R^{f})$	2.31	**2.32**	2.34	2.36
$\sigma(R^{f})$	2.88	**0.20**	0.19	0.16
$\mathbb{E}[R_{ex}^{LEV}]$	5.72	**1.49**	1.35	1.31
$\sigma(R_{ex}^{LEV})$	14.72	**4.63**	4.51	4.47

Notes: This table reports the main moments for the benchmark calibration (specification [1]) and two other model specifications. In models [2] and [3], temperature risk affects the macro economy differently than in the benchmark model. In specification [1], temperature affects the obsolescence rate of patents, i.e. as in Equation (29) with $\tau_T = -0.008$, in specification [2] as in Equation (46) with the same $\tau_T = -0.008$, while in specification [3], temperature effects are shut down, i.e, $\tau_T = 0$. The aggregate market return is levered as in Croce (2014). Models' entries are obtained from repetitions of small-sample simulations (i.e. averages over 3000 simulations of 41 years). $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot,\cdot)$ denote mean, volatility, and correlation, respectively, and $\partial \Delta s^{*}/\partial \varepsilon_T$ denotes the initial response of R&D expenditure growth to a one standard deviation shock in temperature in percentage points. Means and standard deviations are expressed in percentage points. Data on global temperature and G7 macro-aggregates are from the Climate Research Unit and the OECD, respectively. Data are annual and run from 1975 (or later) to 2014. Additional details on the data are provided in Appendix A.

Table C.9: Welfare Costs of Temperature Risk (Different Temperature Risk)

	$[\tau_T = 0]$	$[\tau_T = -0.00901]$
$\mathbb{E}(\hat{U})$	0.5865	0.5581
Δ	—	5.09%

Notes: This table reports the welfare costs of temperature shocks for the specification where temperature risk affects the macro economy differently in contrast to the benchmark model, i.e. as in Equation (46), but with the same $\tau_T = -0.008$. Welfare costs are defined as the percentage increase $\Delta > 0$ in time-zero utility bundle units that the household should receive in order to be indifferent between living in an economy with full risk exposure (i.e. $\sigma_T, \sigma_a, \sigma_g > 0$) and an economy without temperature effects. Temperature effects are eliminated by imposing $\tau_T = 0$.

Table C.10: Long-run Effects of Temperature Shocks (Different Temperature Risk)

Panel A: Single Transitory Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_T	−0.11	−0.36	−0.55	−0.70	−0.77
2 std. dev. σ_T	−0.22	−0.73	−1.09	−1.40	−1.54
Panel B: Multiple Transitory Shocks — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1981–2014	1981–2030			
obs. shocks 1981–2014	0.24	−0.38			
Panel C: Permanent Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	16Y				
0.379°C	−9.97				

Notes: Panel A of this table reports the cumulative change in output growth over 1, 5, 10, 20, and 50 years in percentage points after a temporary temperature shock for the specification where temperature risk affects the macro economy differently in contrast to the benchmark model, i.e. as in Equation (46) with $\tau_T = -0.008$. The cumulative growth in an economy without such a shock is compared to that in an economy with shocks to temperature (i.e. with $\varepsilon_t > 0$). Specifically, we report $(\sum_{j=1}^{N} \Delta y_{t+j}) - N \cdot \Delta y^*$ where Δy_{t+j} is the log growth rate of total output, and Δy^* is the steady state growth rate in the economy without a shock (i.e. with $\varepsilon_t = 0$). For example, the entry −0.44 for a horizon of 5 years in the first row means that cumulative output growth over these 5 years has been 0.44 percentage points lower than it would have been without the temperature shock. The amount of lost output growth is reported for temperature shocks amounting to one and two standard deviations, i.e. to 0.12°C and 0.24°C, respectively. Panel B reports the cumulative change in output growth if the observed shocks to global temperature (both positive and negative shocks) in the period 1981–2014, backed out from the data by using the definition $\varepsilon_{T,t} = T_{G,t} - T_{G,t-1}$, are used in the model simulation. For the entry under the heading "1981–2030", it is assumed that there are no shocks after 2014. Therefore, the additional cumulative change in output growth is due to the persistent effects of temperature shocks on the patent obsolescence rate that still affect the model years 2014–2030. Panel C reports the cumulative change in output growth for a period of 16 years after a permanent global temperature shock, translating into a permanent increase of the patent obsolescence rate (i.e. we assume $\rho_\theta = 1$). The observed global temperature change, used as the permanent shock, is calculated by subtracting the average global temperature for the first 10 years of the data (1981–1990) from the average global temperature of the last 10 years of data (2005–2014). This calculation gives rise to a change in global temperature of 0.379°C.

C.5 Different temperature risk 2

Table C.11: Simulated Moments (Different Temperature Risk 2)

Variable	**Data**	**Benchmark**	$\tau_T < 0$	$\tau_T = 0$
		[1]	**[2]**	**[3]**
MACRO QUANTITIES				
$\mathbb{E}(\Delta c^*)$	2.25	**2.25**	2.28	2.25
$\sigma(\Delta y)$	1.60	**1.60**	1.60	1.59
$\sigma(\Delta c^*)$	1.20	**1.14**	1.08	1.07
$\sigma(\Delta c^*)/\sigma(\Delta y)$	0.75	**0.71**	0.68	0.68
$\sigma(\Delta i^*)/\sigma(\Delta y)$	2.05	**1.05**	1.05	1.03
$\sigma(\Delta s^*)/\sigma(\Delta y)$	1.92	**1.95**	1.91	1.92
$\rho(\Delta c^*, \Delta y)$	0.87	**0.65**	0.69	0.70
$\rho(\Delta c^*, \Delta i^*)$	0.81	**0.66**	0.73	0.76
$\rho(\Delta i^*, \Delta y)$	0.93	**0.99**	0.99	0.99
$\rho(\Delta s^*, \Delta y)$	0.59	**0.98**	0.98	0.99
$\rho(\Delta s^*, T)$	-0.46	**-0.11**	-0.09	0.00
$\partial \Delta s^* / \partial \varepsilon_T$	-0.57	**-0.62**	-0.18	0.00
TEMPERATURE				
$\mathbb{E}(T)$	14.27	**14.27**	14.27	14.27
$\sigma(T)$	0.23	**0.23**	0.23	0.23
ASSET PRICES				
$\mathbb{E}(R^f)$	2.31	**2.32**	2.35	2.36
$\sigma(R^f)$	2.88	**0.20**	0.18	0.16
$\mathbb{E}[R_{ex}^{LEV}]$	5.72	**1.49**	1.44	1.31
$\sigma(R_{ex}^{LEV})$	14.72	**4.63**	4.62	4.47

Notes: This table reports the main moments for the benchmark calibration (specification [1]) and two other model specifications. In models [2] and [3], temperature risk affects the macro economy differently than in the benchmark model. In specification [1], temperature affects the obsolescence rate of patents, i.e. as in Equation (29) with $\tau_T = -0.008$, in specification [2] as in Equations (47)–(49) with the same $\tau_T = -0.008$, while in specification [3], temperature effects are shut down, i.e, $\tau_T = 0$. The aggregate market return is levered as in Croce (2014). Models' entries are obtained from repetitions of small-sample simulations (i.e. averages over 3000 simulations of 41 years). $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot,\cdot)$ denote mean, volatility, and correlation, respectively, and $\partial \Delta s^* / \partial \varepsilon_T$ denotes the initial response of R&D expenditure growth to a one standard deviation shock in temperature in percentage points. Means and standard deviations are expressed in percentage points. Data on global temperature and G7 macro-aggregates are from the Climate Research Unit and the OECD, respectively. Data are annual and run from 1975 (or later) to 2014. Additional details on the data are provided in Appendix A.

Table C.12: Welfare Costs of Temperature Risk (Different Temperature Risk 2)

	$[\tau_T = 0]$	$[\tau_T = -0.00901]$
$\mathbb{E}(\hat{U})$	0.5865	0.5659
Δ	—	3.64%

Notes: This table reports the welfare costs of temperature shocks for the specification where temperature risk affects the macro economy differently in contrast to the benchmark model, i.e. as in Equations (47)–(49), but with the same $\tau_T = -0.008$. Welfare costs are defined as the percentage increase $\Delta > 0$ in time-zero utility bundle units that the household should receive in order to be indifferent between living in an economy with full risk exposure (i.e. $\sigma_T, \sigma_a, \sigma_g > 0$) and an economy without temperature effects. Temperature effects are eliminated by imposing $\tau_T = 0$.

Table C.13: Long-run Effects of Temperature Shocks (Different Temperature Risk 2)

Panel A: Single Transitory Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_T	−0.14	−0.43	−0.68	−0.98	−1.31
2 std. dev. σ_T	−0.28	−0.86	−1.35	−1.97	−2.61
Panel B: Multiple Transitory Shocks — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	1981–2014	1981–2030			
obs. shocks 1981–2014	−0.42	−1.72			
Panel C: Permanent Shock — Cumulative change in output growth $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$					
Shock size	16Y				
0.379°C	−9.97				

Notes: Panel A of this table reports the cumulative change in output growth over 1, 5, 10, 20, and 50 years in percentage points after a temporary temperature shock for the specification where temperature risk affects the macro economy differently in contrast to the benchmark model, i.e. as in Equations (47)–(49) with $\tau_T = -0.008$. The cumulative growth in an economy without such a shock is compared to that in an economy with shocks to temperature (i.e. with $\varepsilon_t > 0$). Specifically, we report $(\sum_{j=1}^{N} \Delta y_{t+j}) - N \cdot \Delta y^*$ where Δy_{t+j} is the log growth rate of total output, and Δy^* is the steady state growth rate in the economy without a shock (i.e. with $\varepsilon_t = 0$). For example, the entry −0.44 for a horizon of 5 years in the first row means that cumulative output growth over these 5 years has been 0.44 percentage points lower than it would have been without the temperature shock. The amount of lost output growth is reported for temperature shocks amounting to one and two standard deviations, i.e. to 0.12°C and 0.24°C, respectively. Panel B reports the cumulative change in output growth if the observed shocks to global temperature (both positive and negative shocks) in the period 1981–2014, backed out from the data by using the definition $\varepsilon_{T,t} = T_{G,t} - T_{G,t-1}$, are used in the model simulation. For the entry under the heading "1981–2030", it is assumed that there are no shocks after 2014. Therefore, the additional cumulative change in output growth is due to the persistent effects of temperature shocks on the patent obsolescence rate that still affect the model years 2014–2030. Panel C reports the cumulative change in output growth for a period of 16 years after a permanent global temperature shock, translating into a permanent increase of the patent obsolescence rate (i.e. we assume $\rho_\theta = 1$). The observed global temperature change, used as the permanent shock, is calculated by subtracting the average global temperature for the first 10 years of the data (1981–1990) from the average global temperature of the last 10 years of data (2005–2014). This calculation gives rise to a change in global temperature of 0.379°C.