How Costly is Global Warming? Implications for Welfare, Business Cycles, and Asset Prices.

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Abstract

We quantify the relative importance of temperature shifts on long-run productivity growth within a production economy framework featuring actual global temperature dynamics and labor market frictions. Our quantitative analysis shows that both output and labor productivity are adversely affected by temperature increases. Such adverse effects are long-lasting. Over a 50 year horizon, a one standard deviation temperature shock lowers both cumulative output and labor productivity growth by 0.5%. In addition, temperature risk generates sizable welfare costs. These amount to 12% of the agent's lifetime utility and grow exponentially with the impact of global temperature on aggregate productivity.

JEL classification: E30, G12, Q0

Keywords: Global warming, long-run growth, asset prices, welfare costs

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1 Introduction

It is widely believed that our entire planet is undergoing climate change. Nevertheless, despite a debate extending over decades by now, a consensus about the long-term economic effects of this dramatic development has not yet been reached among economists (see Pindyck, 2013). In this regard, our paper provides a first step towards the quantification of the extent to which temperature shifts affect aggregate productivity, labor, and, consequently, aggregate consumption. More specifically, we integrate time-varying temperature dynamics into a production-based model featuring recursive preferences, investment adjustment costs, and labor market frictions. This setup provides us with the opportunity to expand the scope of the analysis considerably beyond what is possible in an endowment-based model, e.g., when it comes to the dynamics of investment and labor.

We calibrate our model to data on the evolution of global temperature and use it to estimate the associated welfare losses. Our findings show that, in the long-run, global warming has strong adverse effects on key macroeconomic aggregates, productivity, and asset valuations. As indicated above, a further important contribution to the literature our model makes is to provide a theoretical equilibrium explanation for the negative effect of global warming on labor productivity found in the data (see DARA, 2012).

Greenhouse gas emissions due to human activities are the most important cause of the climatic developments that followed the Industrial Revolution in 1750 (Hartmann, Klein Tank, Rusticucci, Alexander, Brönnimann, Charabi, Dentener, Dlugokencky, Easterling, Kaplan, Soden, Thorne, Wild, and Zhai, 2013). Greenhouse gases affect atmospheric composition, leading to a rise in surface temperature on earth which, in turn, increases the probability of certain types of extreme weather events (e.g., heavy rainfalls, floods, hurricanes, or droughts), as shown by, e.g., Pall, Aina, Stone, Stott, Nozawa, Hilberts, Lohmann, and Allen (2011), Emanuel (2013), and Villarini, Smith, and Vecchi (2013).

Several studies investigate the linkage between weather events and economic performance. Hsiang (2010) documents that industries such as agriculture and tourism, where relocation is either completely impossible or at least extremely expensive, are affected most by higher temperatures and increasing rainfall. Brückner and Ciccone (2011) show that rainfall affects economic output, while Hsiang, Burke, and Miguel (2013) report a positive relation between anthropogenic climate change and human conflict. Higher temperatures have non-linear effects on crop yields, i.e., above a certain threshold higher temperatures no longer increase yields, but are extremely detrimental (Schlenker and Roberts, 2009). Furthermore, higher temperatures lead to an increase in mortality (Deschênes and Moretti, 2009), a reduction in labor supply (Zivin and Neidell, 2014), and a general decrease in productivity and performance (Cachon, Gallino, and Olivares, 2012). Cattaneo and Peri (2016) argue that large temperature increases negatively affect agricultural productivity, which has different consequences on emigration rates depending on the country's income level, with emigration rates in middle-income countries significantly higher than those in poor countries.

Pricing the risks associated with climate change is essential for comparing the costs for different measures to contain the adverse climatic developments. A popular approach is to use so-called integrated assessment models (IAMs) (e.g., Stern, 2007; Nordhaus, 2008; Golosov, Hassler, Krusell, and Tsyvinski, 2014). However, the usefulness of these models in estimating the social cost of climate change and increasing carbon emissions is at the center of an ongoing debate. For example, Pindyck (2013) criticizes IAMs as having little theoretical or empirical foundation. He finds that the model inputs, such as parameter values and functional forms, are chosen arbitrarily, while the choice of the discount rate reaches an ethical dimension.[1] Furthermore, he stresses that the majority of economic studies on climate change imposes a loss function on the level instead on the growth rate of output. This assumption does not seem appropriate, since climate change is likely to have a permanent economic impact (e.g., through the destruction of ecosystems, deaths from weather extremes, or social disruption), and it also contradicts the empirical findings provided by Dell, Jones, and Olken (2012). Furthermore, according to Revesz, Howard, Goulder, Kopp, Livermore, Oppenheimer, and Sterner (2014), current models omit adverse effects on labor productivity, productivity growth and the value of the capital stock.

Our model addresses the issues raised by these critics in a straightforward way. It builds on the production economy framework of Croce (2014), who shows that long-run productiv-

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[1] According to Pindyck (2013) one might argue that it is unethical to value the welfare of future generations relative to our own welfare. In this case, the discount rate should equal zero. However, Nordhaus (2007) and Weitzman (2007) argue that this assumption is inconsistent with actual individual behavior.

ity risks coupled with preferences for early resolution of uncertainty have strong implications for asset prices and macroeconomic quantities. We augment the model in Croce (2014) by temperature dynamics as suggested by Bansal and Ochoa (2011a) and by sticky wages as proposed by Uhlig (2007). Specifically, temperature shocks negatively impact the long-run productivity growth in the economy, and this assumption is strongly supported by the empirical evidence. A bivariate vector autoregression (VAR) analysis, which includes global total factor productivity (TFP) and global temperature dynamics, confirms this overall negative impact of rising temperatures on productivity growth. More precisely, we observe that a one standard deviation global temperature shock gives rise to a drop in aggregate TFP of around 0.3% for the G7 countries. The observed effect is statistically significant and long-lasting. This type of link between temperature and TFP makes sure that the impact of temperature is actually on the growth rate of macro-aggregates, not on their level. Furthermore, in our general equilibrium framework the agent chooses her labor input optimally, so that we can also investigate the potential effects of temperature changes on labor productivity.

Our production-based asset pricing model integrating climate change is then parametrized based on the results from the VAR analysis and by a set of parameter values able to match asset prices, macroeconomic quantities and global temperature statistics. The detailed analysis of the model output shows that an adverse temperature shock simultaneously generates a substitution and an income effect which work in opposite directions. A rapid temperature increase decreases the opportunity cost of consumption. The substitution effect then means that such a temperature shock reduces long-run productivity and consequently makes saving and investing less profitable, so that the agent prefers to increase consumption and decrease investment. The income effect, on the other hand, is caused by the negative impact of temperature on long-run productivity. In this case, the agent feels poorer due to the lower the value of future output and decides to reduce her current consumption. Whether the income or the substitution effect dominates depends on the households' intertemporal elasticity of substitution. When the intertemporal elasticity of substitution is sufficiently high, the substitution effect dominates, such that in the short run consumption will increase at the expense of investment. In the long-run, however, temperature innovations will always negatively impact both consumption and output growth, which leads to lower asset valuations. We also observe negative effects on labor productivity growth in the long-run, since there are long-run output losses, and the agent needs to work more in order to compensate for the lower TFP. An important feature of our model is thus that it endogenously generates the negative effect of global warming on labor productivity found in the data (DARA, 2012). Finally, when we express the economic costs of higher temperatures in terms of consumption needed to compensate the agent for temperature risk, we find that welfare costs are quite sensitive to the degree to which temperature changes impact TFP growth. Increasing the negative impact of temperature in absolute terms makes welfare costs go up exponentially, which provides further evidence for the dramatic impact that climate change can have on global economic well-being. Specifically, welfare costs amount to 12% of composite consumption for our base-case parametrization, but if we allow for higher temperature adverse effects, which are still in the range of empirical estimates, those costs can easily go up to us much as 40%.

The remainder of this study is organized as follows. Section 2 provides empirical evidence on the effects of global warming on aggregate productivity. Section 3 presents the model. The benchmark calibration and main quantitative results are presented in Sections 4 and 5, respectively. Section 6 concludes.

2 Temperature Dynamics and Productivity: Some Empirical Facts

Global warming has received increasing attention among scientists and policymakers during the last two decades. Needless to mention, global warming is still at the center of political debates in the US as well as in many other countries.[2] This attention has been driven by the empirical evidence on global temperature dynamics. Using NASA data, the six pictures in Figure 1 show the evolution of global temperatures over the last close to 100 years. The

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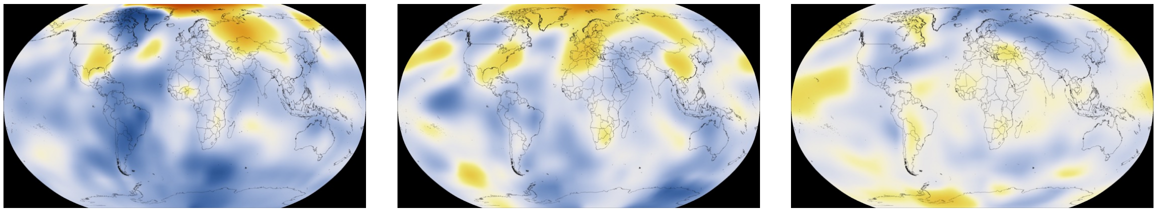
[2] In the US election campaign 2016, this is still a controversial topic among Democratic and Republican candidates. While Donald Trump supposedly does not believe in man-made climate change (www.washingtonpost.com/news/energy-environment/wp/2016/03/22/this-is-the-only-type-of-climate-change-donald-trump-believes-in), Hillary Clinton is a strong proponent of climate change action (www.hillaryclinton.com/issues/climate).

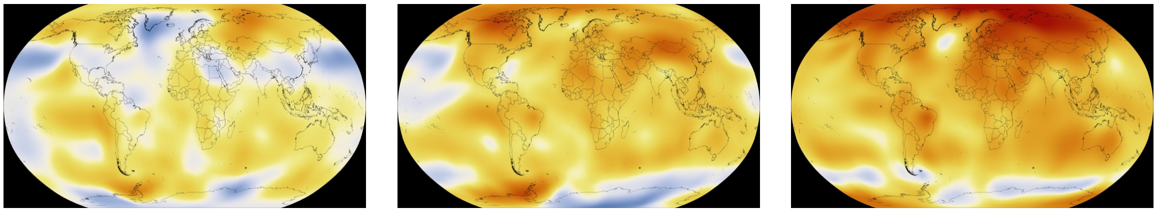
first thing to notice is that the speed of global warming has increased dramatically. While the change from 1925 to 1970 appears modest, temperature increases became much more pronounced over the past 30 years, as can be seen from a comparison of Panels A, B, and C to Panels D, E, and F in Figure 1. The most dramatic increase is observed over the last 15 years, as indicated by a comparison of Panels E and F. The situation at the beginning of the 21st century is entirely different from the one observed 90 years ago. As shown in Panel A of the same figure, at the beginning of the 20th century, hardly any area was displaying relatively high temperature. Similar conclusions can be drawn from Figure 2 that presents the evolution of the Global Temperature Anomaly Index. The plot reveals that the ten warmest years occurred over the period 2000-2015 and that the upward trend is still continuing. As a matter of fact, 2015 was the warmest year overall.

Figure 1: Global Temperature Anomalies

Panel A: 1925 Panel B: 1950 Panel C: 1970



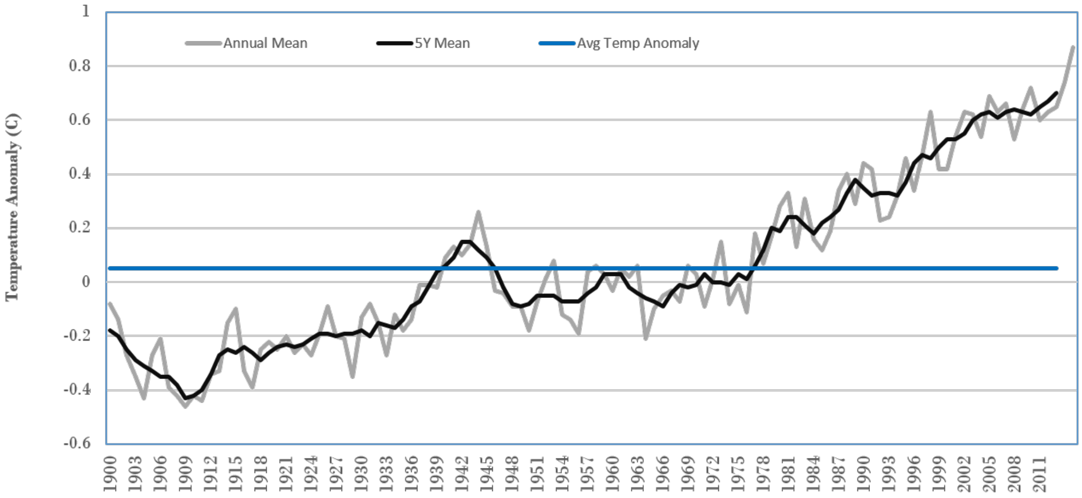
Panel D: 1985 Panel E: 2000 Panel F: 2015



Notes: This figure depicts global temperature anomalies (i.e., five-year average variation of global surface temperatures) in different years. Dark blue indicates areas cooler than average. Dark red indicates areas warmer than average. Temperature differences are measured in degrees Fahrenheit ($^\circ F$). Scale: -4$^\circ F$ (dark blue) / +4$^\circ F$ (dark red). Source: NASA's Goddard Institute for Space Studies.

A number of studies has shown that temperature increases harm real economic activity (e.g., Bansal and Ochoa, 2011a; Dell, Jones, and Olken, 2012; Colacito, Hoffmann, and Phan, 2016). We contribute to this evidence by showing novel results for the impact of temperature increases on TFP. For this purpose, we estimate a bivariate VAR model featuring a measure for aggregate TFP of the G7 countries and global temperature dynamics. Data on global surface temperature are obtained from the Climate Research Unit. The proxy for G7 TFP is computed by employing data from the EU KLEMS Growth and Productivity Accounts for the period 1973-2009 (O'Mahony and Timmer, 2009). This database includes measures of output and input growth, and derived variables such as multifactor productivity at the industry level. Its main purpose is to generate internationally comparative productivity trends. This fact is crucial for our analysis since we are interested in the aggregate effect of global warming on the G7 countries. Additional details concerning the data are provided in Appendix A.

Figure 2: Global Temperature Anomaly Index (1900-2015)



Notes: This figure illustrates the change in global land-ocean temperature relative to 1951-1980 average temperatures. The blue line indicates the average temperature anomaly. Source: NASA's Goddard Institute for Space Studies.

Panel A in Figure 3 depicts the impulse-response function of G7 TFP growth to a shock in global temperature. In line with existing evidence, we observe that a global temperature shock reduces TFP growth. The negative effect is rather persistent, lasting for more than ten years and is statistically significant at the 10% level.[3] The point estimate suggests that a one standard deviation global temperature shock reduces TFP growth by -0.3% on impact. Given the 90% confidence bands, the response of TFP growth could also amount to -0.6%.

To account for possible side effects of global warming, i.e., for weather-related phenomena

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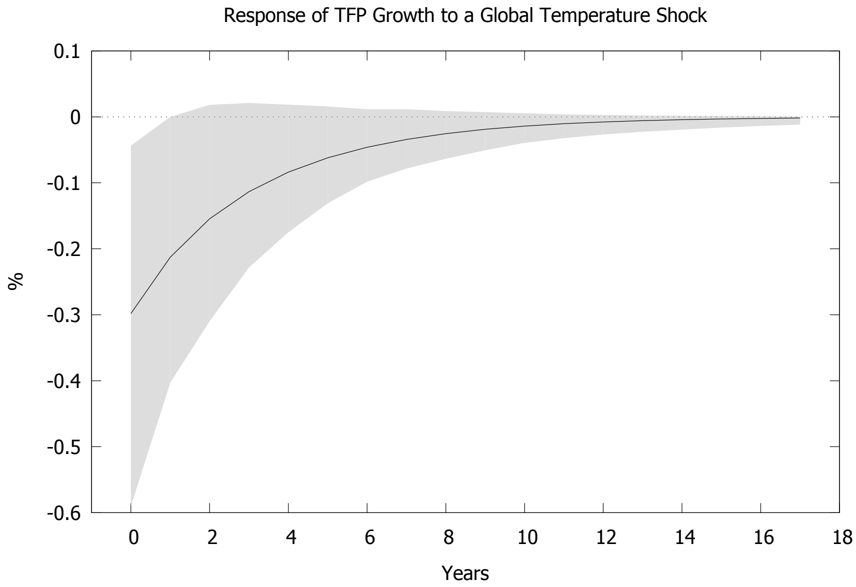
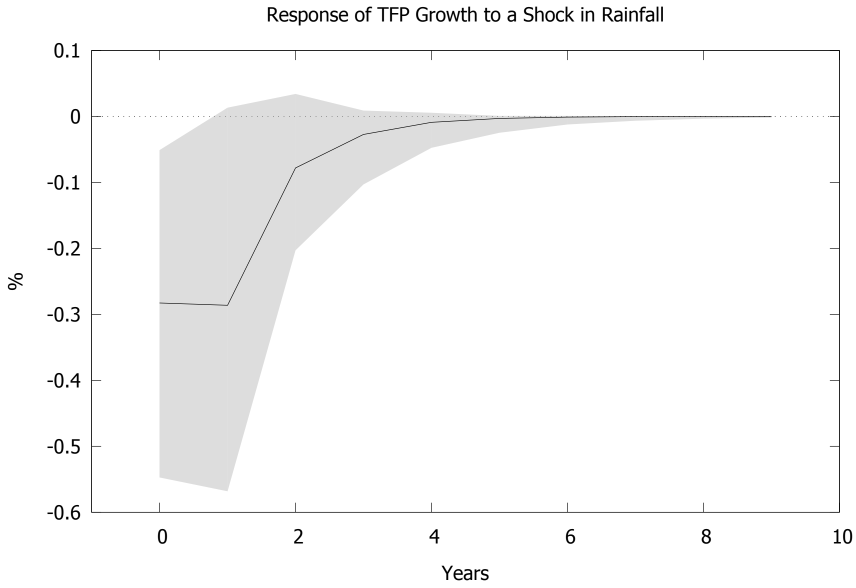
[3] To examine whether there is a bi-directional relationship between aggregate productivity and temperature we run a set of Granger causality tests. For TFPs obtained from the EUKLEMS database it appears that Granger causality (with three lags) runs one-way from temperature to TFP and not the other way. Results are available upon request.

Figure 3: Global Temperature, Rainfall and Productivity

Panel A:


Response of TFP Growth to a Global Temperature Shock

Panel b:


Response of TFP Growth to a Shock in Rainfall

Notes: This figure reports orthogonalized impulse responses to global temperature (Panels A) and rainfall shocks (Panel B). The solid lines represent the point estimates. The shaded areas identify bootstrap confidence intervals at 90% level. The bivariate VARs are estimated including a constant. Lags have been selected according to the Bayesian Information Criterion (BIC). Global temperature and rainfall are expressed in levels, whereas productivity growth rates are expressed in percent deviations from their long-run mean. The horizontal axis identifies years. The TFP series in Panels A and B is computed as a simple average of the G7 TFP growth series. TFP data are from the EU KLEMS database (Sample: 1973-2009). Data on global temperature are from the Climate Research Unit database. Rainfall data are from the Climate Change Knowledge Portal of the World Bank.

other than rising temperatures, we also look at aggregate rainfall in the G7 countries and its effect on TFP in Panel B of Figure 3. Global warming increases the atmosphere's water-holding capacity, and recent climate research suggests that this will lead to an overall increase in rainfall and extreme precipitation (see e.g., Donat, Lowry, Alexander, O'Gorman, and Maher., 2016; Min, Zhang, Zwiers, and Hegerl., 2011). This, in turn, raises the risk of floods, which then might cause economic and social disruptions. Although research suggests that global precipitation is increasing with global warming, regional and seasonal effects can even go in the opposite direction, but be just as important. For instance, dry regions might become even drier while wet regions can become even wetter (Marvel and Bonfils, 2013). This not only raises the likelihood of floods but also that of dry periods, thus, harming in particular those economies that depend heavily on agriculture. Examples for economic studies that deal with the effects of rainfall and economic growth include Barrios, Bertinelli, and Strobl. (2010), Masters and Sachs (2001), and O'Connell and Ndulu (2000).

To shed further light on the relationship between global warming, rainfall and real economic activity, we estimate a bivariate VAR of annual G7 TFP and rainfall analogous to the one for temperature and TFP. Data on rainfall are taken from the Climate Change Knowledge Portal (CCKP) of the World Bank. Details can be found in Appendix A. The results suggest that there is a negative overall effect of higher rainfall on TFP, although it appears slightly less persistent than that of global temperature. The response is also statistically significant at the 10% level. Although other weather-related phenomena like increasing rainfall, droughts, storms, or natural disasters in general will certainly have a non-negligible impact on the aggregate economy we do not model them explicitly. We strongly believe that we capture the first order effect of global warming by looking at temperature dynamics as a broad weather indicator, since natural disasters are known to be triggered via excessively increasing global temperatures.[4]

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[4] The extension of our production-based model by adding natural disasters is left for future research.

3 Model

In the following subsections, we develop a dynamic stochastic general equilibrium (DSGE) model that allows us to study the effects of global warming on the real economy and financial markets. We augment the model suggested by Croce (2014) who introduces long-run productivity risk in a production economy, by a stochastic process for temperature along the lines of Bansal and Ochoa (2011a), which is coupled with the evolution of TFP. As observed in the data, a rising temperature has a negative impact on long-run productivity growth and therefore affects the real economy and asset prices. In the production sector, the representative firm uses capital and labor to produce the final good that can be either invested or consumed. The representative household owns the firm and has recursive preferences over labor and consumption. The production technology is subject to both short- and long-run productivity shocks. In line with recent studies showing that real labor market dynamics play an important role in bringing both macro-quantities and asset prices closer to their empirical counterparts (see, among others, Uhlig, 2007; Donadelli and Grüning, 2016; Favilukis and Lin, 2016), we also account for wage rigidities.

3.1 Households

The representative household is equipped with recursive preferences, as in Epstein and Zin (1989):

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

$\tilde{C}_t$ is a Cobb-Douglas aggregator for consumption C and leisure $1-L$ (the remainder of a total time budget of 1, when the amount of labor is L):

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

where A denotes TFP. Multiplying leisure by the level of TFP ensures balanced growth and is interpreted as an adjustment for the standard of living (Croce, 2014). In this setting, γ measures risk aversion, ψ is the intertemporal elasticity of substitution (IES), and β is the household's subjective discount factor. In line with the long-run risk literature, we assume that the representative household has preferences for early resolution of uncertainty, i.e., $\gamma > \frac{1}{\psi}$. Notice that under power utility (represented by $\gamma = \frac{1}{\psi}$) the impact of current shocks to productivity growth or temperature is always the same, irrespective of the persistence of these innovations. Loosely speaking, long-run productivity and temperature shocks will not be priced. Differently, under recursive preferences the household cares about uncertainty with respect to future utility and the risk generated by persistent innovations is priced. As a result, long-lasting shocks affect both prices and quantities (see Dew-Becker and Giglio, 2016).

In each period, the representative household chooses consumption C_t and labor L_t to maximize the utility function U_t subject to the following budget constraint:

$$C_t + B_{t+1} + \vartheta_{t+1}(V_t - D_t) = W_t^u L_t + B_t R_t^f + \vartheta_t V_t,$$

where ϑ_t denotes the number of equity shares in the firm held from time $t-1$ to time t, V_t is the cum-dividend market value of the production sector, D_t denotes dividends, B_t is the number of bonds held from time $t-1$ to time t, R_t^f is the gross risk-free rate, and W_t^u represents the frictionless wage (i.e., without wage rigidities, see also Uhlig, 2007). Hence, the household chooses the amount of hours allocated to labor as if wages were not sticky.

The first order conditions of the maximization problem lead to the following expression for the stochastic discount factor (SDF):

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

The usual Euler equations for the cum-dividend value of one share of equity in the production sector and the gross risk-free rate can be written as

$$V_t = D_t + \mathbb{E}_t[M_{t,t+1} V_{t+1}]$$

and

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

3.2 Firms

The production sector admits a representative perfectly competitive firm utilizing capital and labor to produce the output. The production technology is given by

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

where α is the capital share, labor L_t is supplied by the household, and A_t is TFP. The capital stock evolves according to

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

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

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

The firm chooses capital, labor, and investment to maximize firm value:

$$V_t = \max_{L_t, I_t, K_{t+1}} \mathbb{E}_t\Big[\sum_{s=0}^{\infty} M_{t,t+s}D_{t+s}\Big].$$

The net profit (i.e., the dividend) of the firm at any point in time t, D_t, is given by output minus investment and labor costs:

$$D_t = C_t - W_t L_t = Y_t - I_t - W_t L_t.$$

The firm's investment decision leads to

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

where q_t defines the marginal value of standardized capital, which is, in turn, equal to the marginal rate of transformation between new capital and consumption. The firm chooses capital such that

$$1 = \mathbb{E}_t \left[M_{t,t+1} \frac{1}{q_t} \left(\frac{\alpha Y_{t+1} - I_{t+1}}{K_{t+1}} + q_{t+1}(G_{t+1} + 1 - \delta_K) \right) \right].$$

This can be rewritten as

$$1 = \mathbb{E}_t \Big[M_{t,t+1} R_{t+1} \Big], \tag{1}$$

where

$$R_{t+1} = \frac{d_{t+1} + q_{t+1}}{q_t}$$

and

$$d_{t+1} = \alpha \frac{Y_{t+1}}{K_{t+1}} - \frac{I_{t+1}}{K_{t+1}} + q_{t+1} G_{t+1} - \delta_K q_{t+1}.$$

Equation (1) defines the asset price restriction for the gross equity return R_{t+1}, which is defined as the return per unit of (normalized) capital.

3.3 Productivity and Global Warming Dynamics

The productivity growth rate, $\Delta a_{t+1} \equiv \log(A_{t+1}/A_t)$, has a long-run risk component, x_t, and evolves according to

$$\begin{aligned} \Delta a_{t+1} &= \mu_a + x_t + \sigma_a \epsilon_{a,t+1} \\ x_{t+1} &= \rho_x x_t + \tau_z \sigma_z \epsilon_{z,t+1} + \sigma_x \epsilon_{x,t+1}. \end{aligned} \tag{2}$$

The unconditional expected growth rate of log productivity is μ_a. Short-run productivity shocks are induced by $\epsilon_{a,t}$, whereas $\epsilon_{x,t}$ and $\epsilon_{z,t}$ indicate long-run shocks affecting the persistent stochastic component in expected productivity growth x_t.[5] The persistence of long-run productivity shocks is measured by ρ_x.

The shock term $\tau_z \sigma_z \epsilon_{z,t+1}$ is the key innovation in our model relative to standard production-based approaches, since it represents the impact of temperature changes on TFP. $\sigma_z \epsilon_{z,t+1}$ is

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[5] Segal, Shaliastovich, and Yaron (2015) use a similar approach to examine the effects of uncertainty on long-run consumption growth. In their setting, uncertainty is then divided into good and bad volatility components which are found to have opposite impact on aggregate growth and asset prices.

the unpredictable part of the change in temperature z, where z evolves according to

$$z_{t+1} = \mu_z + \rho_z(z_t - \mu_z) + \sigma_z \epsilon_{z,t+1}.$$

The parameter τ_z in (2) captures the direction and the intensity to which unpredictable temperature shocks impact long-run productivity growth. Based on our empirical analysis discussed in Section 2, we assume $\tau_z < 0$ when we study the quantitative implications of the model, i.e., temperature shocks have a negative impact on on long-run expected productivity growth. Whereas temperature has an impact on TFP growth, we assume that there is no effect in the opposite direction, i.e., productivity shocks do not affect temperature.[6]

3.4 Labor Market

On the side of the firm, the optimal labor allocation leads to

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

which means that the wage rate paid by the firm must equal the marginal product of labor. The household's optimal labor allocation leads to

$$W_t^u = \frac{1 - \nu}{\nu}\Big(\frac{C_t}{1 - L_t}\Big),$$

which means that the marginal rate of substitution between consumption and leisure should equal the wage rate that the household receives.

In standard production models, wage volatility tends to be too high, while equity volatility is usually too low. To bring our model closer to the data, we assume that labor supply is subject to frictions. The inclusion of sticky wages leads to smoother wages and reduces procyclicality of labor but comes at the cost of higher volatility of labor (see e.g., Favilukis and Lin, 2016; Donadelli and Grüning, 2016). In the spirit of Uhlig (2007), we assume that a fraction of the total labor supply does not reach the market. This results in sticky wages

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[6] This is consistent with empirical evidence suggesting that temperature shocks affect global productivity growth, but not vice versa.

represented as

$$W_t = (e^{\Delta a_t} W_{t-1})^{\xi} (W_t^u)^{1-\xi},$$

where ξ measures the degree of labor market frictions. This structure for wages constitutes a way to model their slow adjustment without having to assume the exact nature of labor market frictions.

3.5 Resource Constraint

The output produced by the firm can be either consumed by the household or invested by the firm. Therefore, goods market clearing implies that

$$Y_t = C_t + I_t.$$

The equilibrium conditions of the model are summarized in Appendix B.

4 Calibration

The model is calibrated to a monthly frequency. Most of the parameters are set in accordance with the long-run risk literature and are chosen to match the dynamics of global temperature observed in the data. Specifically, we set the subjective discount factor, β, the coefficient of relative risk aversion, γ, and the elasticity of intertemporal substitution (IES), ψ, to values of 0.999, 7.5 and 1.85, respectively. Note that these values for γ and ψ imply that the agent has preference for the early resolution of uncertainty.

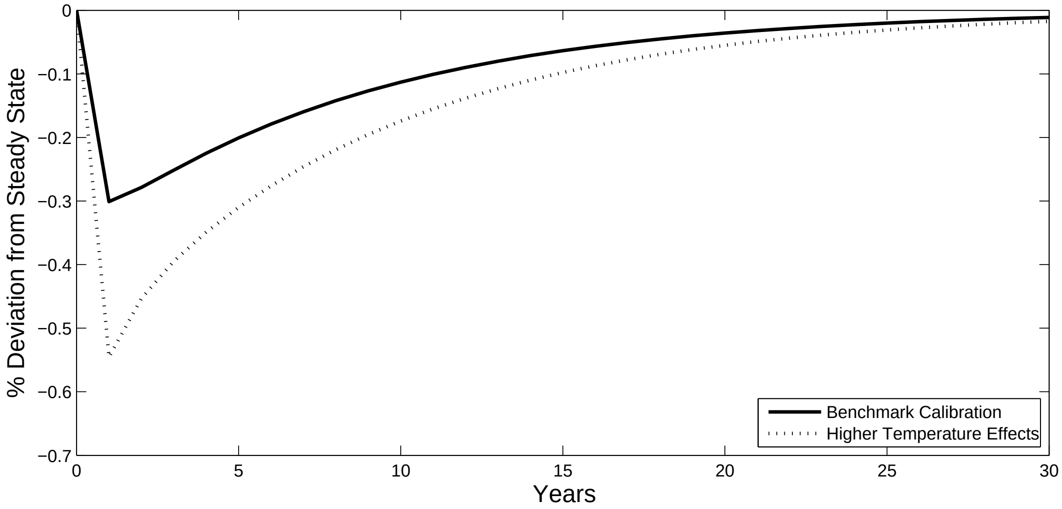
The consumption share in the utility bundle $\tilde{C}$ is chosen such that the steady state supply of labor is one third of the total time endowment of the household (see Donadelli and Grüning, 2016). Given the other parameters, this is achieved by setting $\nu = 0.3484$. The parameter ξ governing wage rigidity is set to 0.35 as in Uhlig (2007).

Concerning the parametrization of the long-run risk process x_t, we set $\rho_x = 0.982$ as in Croce (2014). The long-run mean of productivity is set to 0.0004, so that the average annual TFP growth rate is 0.05, consistent with the data for the G7 countries. As in Bansal and Yaron (2004) and Croce (2014), we fix the volatility σ_x of the long-run shock to be small relative to the volatility of the short-run shock. In particular, we set $\sigma_x = 0.045 \cdot \sigma_a$, where $\sigma_a = 0.008$.

On the production side, we set the capital share α in the production technology equal to 0.345 as in Croce (2014). Regarding the adjustment cost parameters, τ is set to 0.7 as in Kung and Schmid (2015). The constants α_1 and α_2 are chosen such that there are no adjustment costs in the deterministic steady state. The depreciation rate of capital δ_K is set to 0.005 as in Croce (2014).

The parameters regarding the temperature process are set to match the global temperature statistics observed in the data over the period 1961-2015. This results in $\mu_z = 14.18$ and $\sigma_z = 0.041$.

Figure 4: Model-Implied Response of Productivity to a Temperature Shock



Notes: This figure shows annual log-deviations from the steady state of Δa_t in response to a one standard deviation positive global temperature shock implied by a bivariate VAR model. Data are obtained from a long sample simulation of 10,000 observations (i.e. 10,000 months). Annual series are then obtained by aggregating monthly observations.

In order to match the dynamics of global temperature, we set the autoregressive coefficient of temperature ρ_z equal to 0.99, which is the value also used by Bansal and Ochoa (2011a). We choose the parameter τ_z determining the impact of temperature innovations on expected growth to match the empirically observed response of TFP following a temperature shock. Figure 4 depicts the model implied responses of TFP growth for two different values of τ_z. Our preliminary empirical VAR analysis suggests that a one standard deviation shock to global temperature (i.e., an increase by 0.24°C) reduces G7 TFP growth by about 0.3% (see Figure 3). In the model, this is achieved by imposing $\tau_z = -0.0025$ in our benchmark scenario. In an alternative scenario, we assume higher temperature effects, i.e. $\tau_z = -0.0045$, to reflect the uncertainty around the negative effects of global warming. In that case, TFP growth drops by more than 0.5% in the model. The size of this TFP response still lies within the confidence bands from the VAR estimation (see Figure 3). The parameter values of our benchmark calibration are presented in Table 1.

Table 1: BENCHMARK CALIBRATION

Parameter	Description	Value
PREFERENCES		
β	Subjective time discount factor	0.999
ψ	Elasticity of intertemporal substitution	1.85
γ	Relative risk aversion	7.5
ν	Consumption share in utility bundle	0.3484
LABOR MARKET		
ξ	Wage rigidity parameter	0.35
PRODUCTION AND INVESTMENT PARAMETERS		
α	Capital share in final good production	0.345
δ_K	Depreciation rate of physical capital	0.005
τ	Capital adjustment costs elasticity	0.7
TFP		
μ_a	Long-run mean of TFP	0.0004
σ_a	Volatility of short-run shocks to TFP	0.008
ρ_x	Long-run TFP shock persistence	0.982
σ_x	Volatility of long-run shocks to TFP	$0.045^*\sigma_a$
GLOBAL TEMPERATURE		
μ_z	Long-run mean of global temperature	14.18
τ_z	Impact of temperature innovations on TFP growth	-0.0025
ρ_z	Temperature persistence parameter	0.99
σ_z	Volatility of shocks to global temperature	0.041

5 Quantitative Results

5.1 The Impact of Temperature Shocks on Macro Quantities and Asset Prices

The main results produced by our benchmark calibration are reported in Table 2 (specification [1]). In line with standard long-run risk models, our framework produces a relatively high equity premium of 3.7% annually and a relatively low risk-free rate of 0.56%, close to what is observed on the major capital markets around the world. The impact of temperature on TFP is responsible for 23 basis points of the total equity premium, since in the case without temperature effects (specification [2]), the equity premium goes down to 3.47%. Equity volatility is slightly higher with temperature in the model, but the difference is not substantial.

The inclusion of temperature risk makes the effects of shifts in global productivity on long-run growth prospects more pronounced, and since the agent has a preference for early resolution of uncertainty, this additional effect is priced. So when the adverse impact of temperature shocks on TFP growth becomes more severe (specification [4] with $\tau_z = -0.0045$), the equity risk premium increases further to a value of around 4.24%.

Similar to other production-based asset pricing models (Croce, 2014; Kung and Schmid, 2015; Donadelli and Grüning, 2016), all our specifications have a certain problem generating a value for equity volatility that is close to that observed in the data, even when a stronger effect of temperature on TFP is assumed. When the representative household has CRRA preferences (specification [3]), temperature risks and long-run risks carry a zero premium. Hence, the model produces basically no equity premium, and it is also not able to generate a risk-free rate as low as observed in the data.

To shed light on the mechanism behind the results concerning the impact of temperature shocks, we look at the responses of selected macro quantities and the SDF to a global temperature shock presented in Figure 5 for the benchmark model [1] (solid line) and specification [4] with a larger impact of temperature on TFP (dotted line). The key feature of our model is that a temperature shock constitutes a negative shock to long-run productivity growth. Figure 4 has shown that this shock is very long-lasting, since the long-run component x of TFP growth is highly persistent, so that it can have a large impact on the agent's long-term consumption and investment plans.

Note that temperature shocks generate both a substitution and an income effect. On the one hand, they lower aggregate productivity and hence the profitability of investment both in the short and the long run. As a consequence, opportunity costs of current consumption decrease and the agent finds it optimal to consume more and invest less (substitution effect).

On the other hand, a lower productivity implies a decrease in the household's continuation value, so that the agent feels poorer and consumes less (income effect). For a given level of output, the income effect tends to raise investment, since lower productivity in the long run increases the required amount of inputs needed for production. Whether the income or the substitution effect dominates depends on the households' intertemporal elasticity of substitution (IES). In our calibration, the IES is greater than 1 and thus sufficiently high for the substitution effect to dominate, as shown in Panels A and B in Figure 5. Consumption increases on impact while investment decreases, and the latter creates a downward pressure on the price of capital. This, in turn, implies a lower firm value and a contemporaneous increase in the stochastic discount factor (see Panel F). Since the negative response of investment is larger in absolute value than the positive reaction of consumption, output falls as well (see Panel C). In the long run, temperature innovations negatively affect both consumption and output growth, which leads to lower asset valuations.

It is important to note that the introduction of temperature risk does not alter the basic properties of the model with respect to standard RBC quantities. Therefore, in our production economy with temperature shocks (i) consumption and labor are less volatile than output; (ii) investment is much more volatile than output and (iii) all macroeconomic aggregates co-move. The inclusion of labor market frictions helps to reduce the procyclicality of labor, but comes at the cost of higher volatility of labor which is in contrast very small in the data. Across all calibrations, the correlation between investment growth and labor growth is relatively low (about 0.2) and matches the observed correlation in the data while volatility of labor growth is relatively high with a value around 1 compared to roughly 0.3 in the data.

To gain more insights on the long-run effects of global temperature shocks, we present the responses of the *expected* growth rates of selected macroeconomic quantities to temperature shocks in Figure 6. As Panel A shows, temperature shocks reduce expected consumption growth, which implies that the short-run increase in consumption growth found in Figure 5 comes at the cost of future consumption growth. Furthermore, there are persistent negative effects on expected output growth as well (see Panel C). In an economy with higher adverse temperature effects, the reactions of expected consumption, investment, and output growth

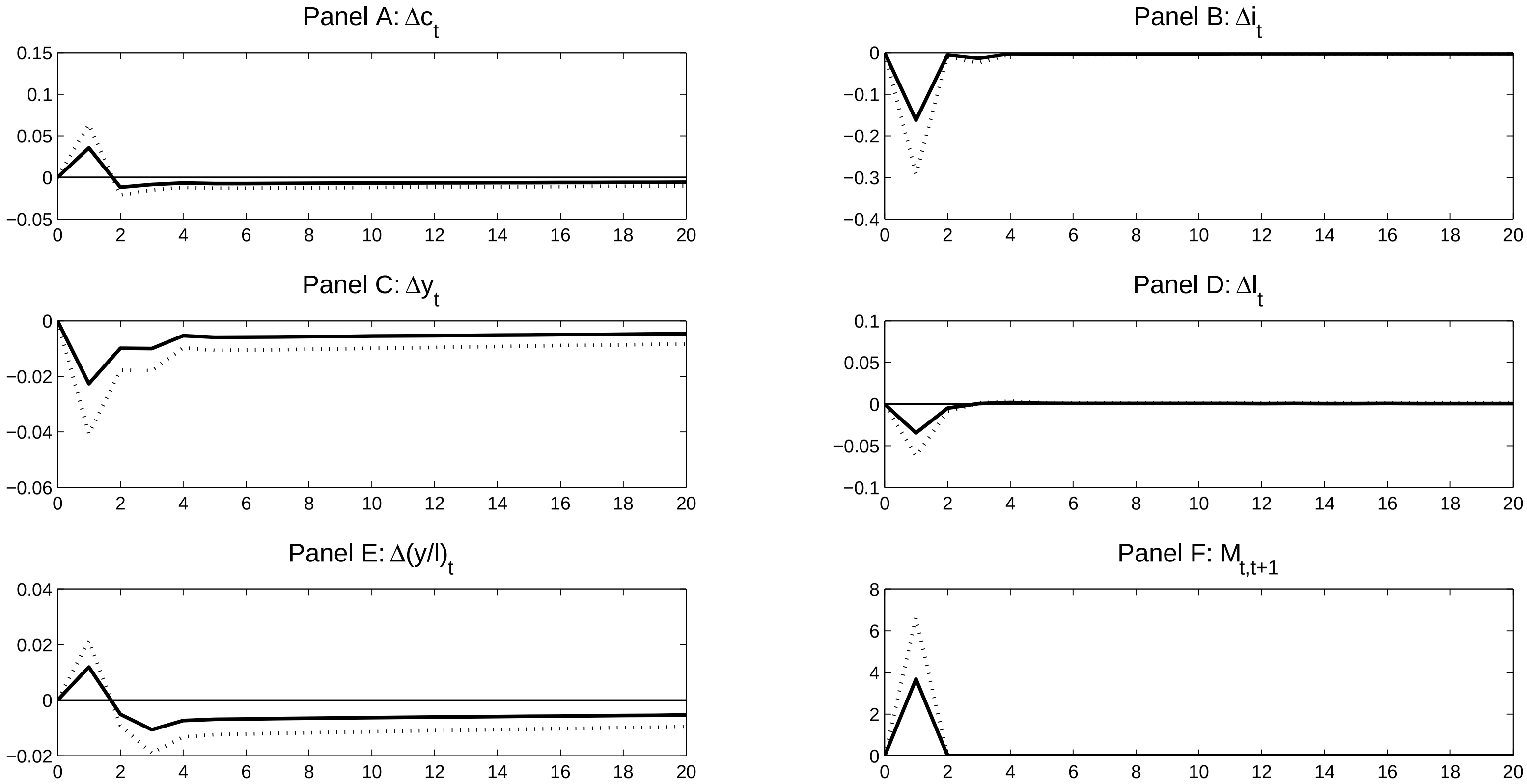
Table 2: Model versus Data: Macroeconomic Quantities and Asset Prices

Variable	**Data**	**Benchmark calibration**	$\tau_z = 0$	**CRRA**	$\tau_z = -0.0045$
		[1]	**[2]**	**[3]**	**[4]**
MACRO QUANTITIES					
$\mathbb{E}[\Delta a]$	0.49	0.51	0.53	0.51	0.50
$\sigma(\Delta l)$	0.28	0.99	0.98	0.99	1.01
$\sigma(\Delta c)/\sigma(\Delta y)$	0.82	0.96	0.96	0.96	0.96
$\sigma(\Delta i)/\sigma(\Delta y)$	2.98	1.90	1.88	1.89	1.92
$\sigma(\Delta l)/\sigma(\Delta y)$	0.19	0.39	0.39	0.39	0.39
$\rho(\Delta c, \Delta y)$	0.90	0.85	0.85	0.84	0.84
$\rho(\Delta c, \Delta i)$	0.73	0.31	0.32	0.31	0.29
$\rho(\Delta i, \Delta l)$	0.24	0.22	0.20	0.23	0.24
TEMPERATURE					
$\mathbb{E}[z]$	14.18	14.19	14.19	14.19	14.19
$\sigma(z)$	0.24	0.24	0.24	0.24	0.24
$\rho(\Delta z, \Delta a)$	-0.01	0.00	-0.01	0.00	0.00
$\rho(\Delta z^{5Y}, \Delta a^{5Y})$	-0.05	-0.05	-0.02	-0.05	-0.06
$\rho(\Delta z^{10Y}, \Delta a^{10Y})$	-0.16	-0.05	0.01	-0.05	-0.10
$\rho(\Delta z, \Delta y)$	-0.03	-0.05	-0.02	-0.05	-0.07
$\rho(\Delta z^{5Y}, \Delta y^{5Y})$	-0.10	-0.05	-0.01	-0.05	-0.07
$\rho(\Delta z^{10Y}, \Delta y^{10Y})$	-0.38	-0.04	0.03	-0.03	-0.08
ASSET PRICES					
$\mathbb{E}[R_f]$	1.54	0.56	0.62	1.47	0.46
$\sigma(R_f)$	2.17	0.56	0.56	0.56	0.57
$\mathbb{E}[R_m - R_f]$	6.93	3.70	3.47	-0.04	4.24
$\sigma(\mathbb{E}[R_m - R_f])$	16.76	6.61	6.47	6.60	6.92

Notes: This table reports the main moments for the benchmark calibration (denoted by [1]) and five other model specifications. In specification [2], we assume that temperature does not affect long-run productivity growth, i.e., $\tau_z = 0$ in Equation (2). Specification [3] assumes CRRA preferences by setting γ equal to $1/\psi$. Specifications [4] and [5] represent cases with a higher or a lower degree of wage rigidity than under the benchmark calibration. In specification [6], temperature shocks are assumed to have a impact on long-run expected productivity growth that is larger in absolute value than under specification [1] ($\tau_z = -0.0045$) Aggregate returns are levered as in Boldrin, Christiano, and Fisher (2001). The model is solved using second-order perturbations around the stochastic steady state in `Dynare++ 4.4.3`. All entries are obtained from repetitions of small-sample simulations. $\mathbb{E}[\cdot]$, $\sigma(\cdot)$ and $\rho(\cdot,\cdot)$; denote mean, volatility, and correlation, respectively. Means and volatilities are annualized and expressed in percentage points. Data on global temperature and macro-aggregates have been retrieved from the Climate Research Unit (University of East Anglia) and World Development Indicators (World Bank), respectively. Data are annual and run from 1961 (or later) to 2015. Additional details on data are provided in Appendix A.

are even stronger, and there are higher long-term losses. Therefore, asset valuations decrease further, and the agent demands an extra compensation for risk.

Figure 5: Responses of Macro Quantities to a Global Temperature Shock



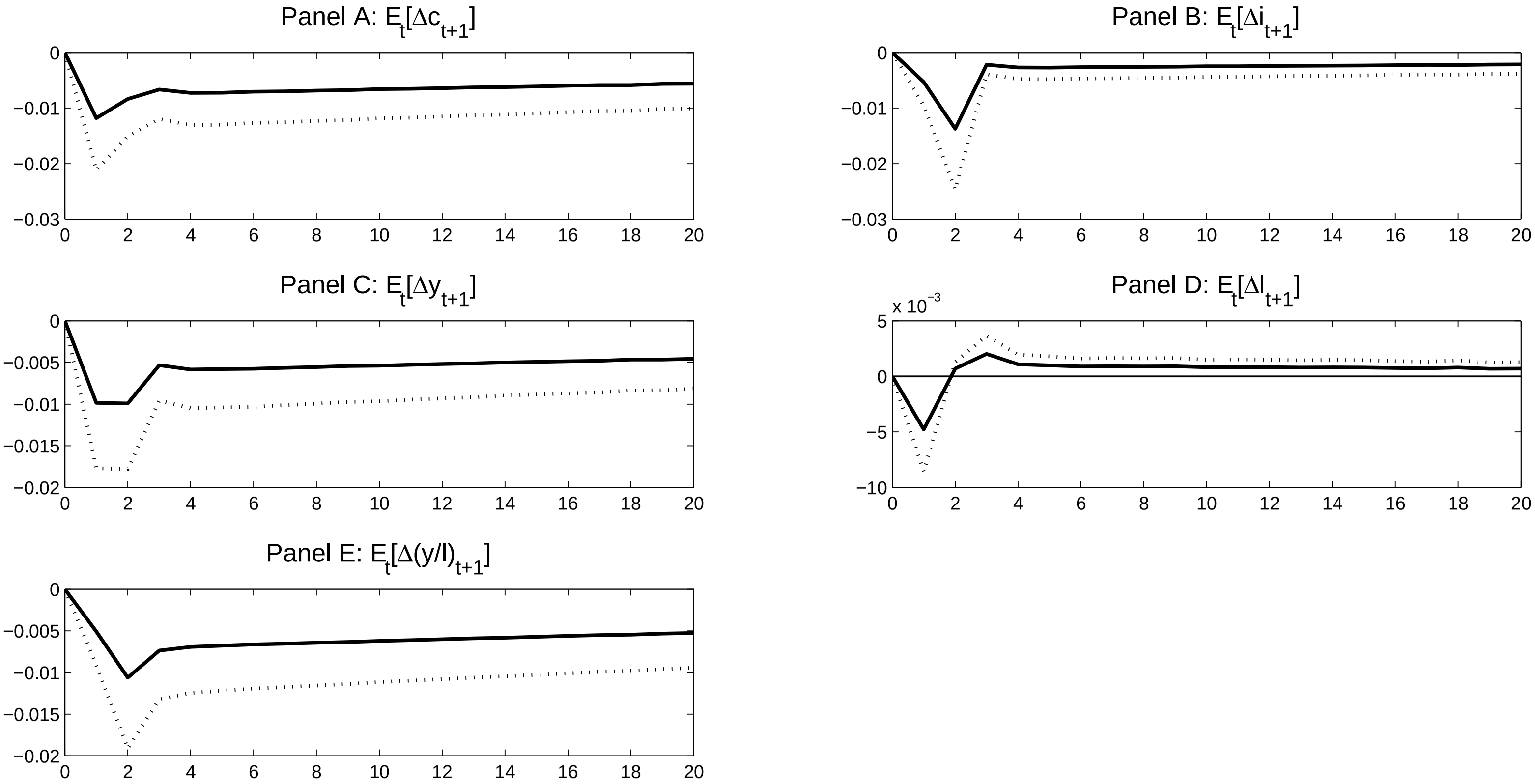
Notes: This figure shows percentage monthly log-deviations from the steady state. Impulse responses of consumption growth Δc_t, output growth Δy_t, investment growth Δi_t, labor growth Δl_t, labor productivity growth $\Delta(y/l)_t$ and the SDF $M_{t,t+1}$ are reported for the benchmark calibration ($\tau_z = -0.0025$, solid lines) and for an economy with higher adverse temperature effects ($\tau_z = -0.0045$, dotted lines).

The key advantage of our model featuring a production sector is that it allows us to analyze the impact of temperature shocks on labor-related quantities. Panels D and E in Figures 5 and 6 present the response of labor L and labor productivity Y/L as well as the respective conditional expectations to such shocks. Panel D in Figure 5 shows that labor decreases in response to a temperature shock. To understand the short-run effect of a temperature shock on labor, note that there are again two forces working in opposite directions. The substitution effect leads to less labor (and more leisure), since the profitability of investment has gone down due to the long-run shock. At the same time, due to the income effect, the household feels poorer, leading to a reduction in leisure and consequently more labor. As we can see, the substitution effect dominates, so that the overall short-run effect is negative. Expected labor growth reacts similarly, but its response is weaker, as one can see from Panel D in Figure 6.

It may seem surprising at first sight that a temperature shock raises labor productivity (i.e., the ratio of total output to labor) in the short run, as shown in Panel E of Figure 5. The reason is that the negative response of labor (Panel D) is larger in absolute value than the one of output (Panel C). In the long run, however, the effect on labor productivity growth is negative due to the positive income effect on labor and persistent output losses. A very important characteristic of our model is that the negative effect of global warming on labor productivity found in the data (DARA, 2012) emerges endogenously. As it was the case for expected consumption growth, expected labor productivity growth already falls on impact (see Figure 6, Panel E). This is because the response of expected labor is weak while there are persistent losses in expected output growth. As expected, when the effects of temperature shocks on productivity become stronger (i.e., when τ_z is larger in absolute value), losses in (expected) productivity growth are also becoming larger.

Taken together, our results suggest that global warming is an important factor for the long-run evolution of key macroeconomic quantities. Its impact is uniformly negative with respect to a wide variety of measures for economic activity, and real asset valuations. In the next section, we provide a first attempt to quantify the losses caused by global warming with respect to long-run output and labor productivity growth. We further compute welfare losses of temperature risk to measure the economic costs of global warming.

Figure 6: Impulse Responses of One-step-ahead Expected Macro Quantities to a Global Temperature Shock



Notes: This figure shows percentage monthly log-deviations from the steady state. Impulse responses of expected output growth $E_t[\Delta y_{t+1}]$, expected consumption growth $E_t[\Delta c_{t+1}]$, expected investment growth $E_t[\Delta i_{t+1}]$, expected labor growth $E_t[\Delta l_{t+1}]$ and expected labor productivity growth $E_t[\Delta(y/l)_{t+1}]$ are reported for the benchmark calibration (solid lines) and for an economy with higher adverse temperature effects $\tau_z = -0.0045$ (dotted lines).

5.2 Temperature Risk, Welfare Costs, and Output Losses

Welfare costs of temperature risk are calculated similarly to Lucas (1987), Bansal and Ochoa (2011b), and Evers (2015). Specifically, they are computed by comparing the agent's utility in an economy with temperature risk to that in an economy without temperature risk. Formally, welfare costs Δ are defined by:

$$\mathbb{E}[U_0((1+\Delta)\tilde{C})] = \mathbb{E}[U_0(\tilde{C}^*)], \tag{3}$$

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

Table 3: TEMPERATURE RISK VS. MACROECONOMIC RISK: A WELFARE ANALYSIS

IES (ψ)	**Benchmark calibration** [1]	$\tau_z = -0.0045$ [2]	**Short-run macro risk** [3]	**Long-run macro risk** [4]
0.90	9%	32%	21%	185%
1.85	12%	44%	27%	299%

Notes: This table reports welfare costs for temperature shocks and short-run as well as long-run macroeconomic shocks for two IES specifications. Welfare costs for each specific source of risk are defined as the percentage increase $\Delta > 0$ in composite consumption ($\tilde{C}$) that the household should receive in every state and at every point in time in order to be indifferent between living in an economy with full risk exposure (i.e., $\sigma_z, \sigma_a, \sigma_x > 0$) and an economy where one of the three risks is shut down. Namely, in specifications [1] and [2] we eliminate temperature risk by imposing $\sigma_z = 0$. Here, the first specification refers to the benchmark calibration (i.e., $\tau_z = -0.0025$) while specification [2] accounts for higher temperature effects (i.e., $\tau_z = -0.0045$). In specifications [3] and [4], we consider the cases without short-run (i.e., $\sigma_a = 0$) or long-run (i.e., $\sigma_x = 0$) productivity shocks.

We compare welfare costs of temperature shocks to the costs of short-run and long-run macroeconomic productivity shocks in order to quantify the importance of temperature risk. Table 3 displays these costs for different scenarios and for two values of the intertemporal elasticity of substitution. We do this to show that our results are qualitatively robust to whether the income ($\psi = 0.90$) or the substitution ($\psi = 1.85$, as in the benchmark case) effect dominates.

In our benchmark calibration the welfare costs are 12% of per capita composite consumption (represented by the bundle consisting of consumption and leisure). This means that the composite consumption of an agent living in an economy with temperature risk needs to be increased by almost an eighth in every state and at every point in time such that the agent has the same utility as in an economy without temperature risk. Hence, the costs of temperature shocks are quite sizable, representing almost half of the costs of short-run macro shocks of 27%. This result is economically plausible, since temperature shocks are found to have a large and persistent impact on productivity and hence on the other macroeconomic variables. Long-run macro shocks are still the most important source of risk with welfare costs of 299% as they exhibit the highest volatility in the long-run risk component of the TFP process.

In the case where TFP growth is more sensitive to temperature shocks ($\tau_z = -0.0045$), welfare costs increase to 44%, which is considerably larger than the costs induced by short-run macro shocks. As shown in Figure 7, it turns out that welfare costs increase exponentially in τ_z. For the largest impact of temperate on TFP shown in the picture ($\tau_z = -0.007$), welfare costs amount to 142% of composite consumption, i.e., compared to the case without temperature risk the representative household would need more than twice the composite consumption to achieve the same utility level.

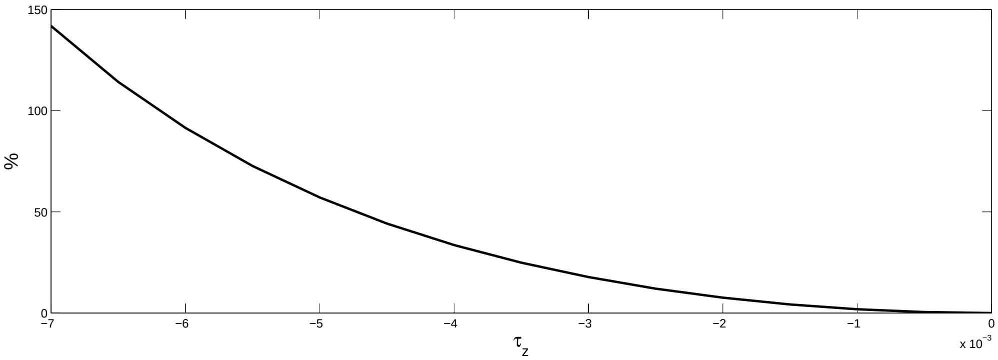
To put our numbers in perspective, we compare them to those obtained by Bansal and Ochoa (2011b) in an endowment economy. In their set up, welfare costs are significantly smaller and amount to only 0.78%. This fact underscores the importance of analyzing global warming in a production economy framework, which explicitly considers the endogenous movements of capital and investment and their impact on asset prices and ultimately on welfare costs. In this regard, investment adjustment costs play a crucial role. Barlevy (2004) shows that welfare costs produced by the volatility of productivity are amplified in economies with capital adjustment costs. Similarly, Croce (2006) finds that, given otherwise identical calibrations, welfare costs in a production economy are higher than those observed in an endowment economy since long-run risk in productivity results in a higher level of long-run uncertainty in the (now endogenous) growth rate of consumption.

The economic mechanism behind the impact of adjustment costs works as follows. When it is costly to change the capital stock, the agent can no longer as easily use investment to decrease the exposure of the consumption process to long-run risk. Adjustment costs generate a negative income effect that reduces both the level and the growth rate of consumption. Given that our calibration with respect to temperature dynamics and preferences is very similar to the one used in Bansal and Ochoa (2011b), one can see from our results that most of the difference in welfare costs can be attributed to effects actually coming from the real side of the economy, in our case from investment.

We can also relate temperature-induced welfare losses to those generated by other significant risks, e.g., oil price shocks as analyzed by Hitzemann and Yaron (2016). They find wealth losses of about 2.5%, which are significantly smaller than the 12% we obtain for our basecase calibration. Obviously this is only a rough comparison, but it nevertheless indicates that temperature risk is a factor significantly affecting an agent's welfare.

The fact that labor is endogenous in our model of course also affects welfare costs. Changing labor hours provides an additional possibility to smooth a productivity shock, implying lower risk premia and welfare costs. Similar to investment adjustment costs, the inclusion of wage rigidities makes it harder to use this smoothing device and thus induces higher overall risk and increasing welfare costs (see Favilukis and Lin, 2016).

Figure 7: Welfare Costs



Notes: This figure reports welfare costs for different values of τ_z. Welfare costs are computed as in Equation (3). All the remaining parameters are set to the values shown in Table 1.

We also analyze welfare costs for a lower value of the IES $\psi = 0.9$. This case is interesting in itself, since macroeconomists and finance researchers do not fully agree as to whether the IES is indeed greater than one or not. In our model a lower IES changes the results quantitatively, but not qualitatively. For the benchmark calibration the welfare loss amounts to 12%, while the corresponding value for the lower IES is 9%. Welfare costs are increasing in the IES, since a higher IES implicitly makes the agent more patient, i.e., future consumption has a higher weight in the value function. Therefore, long-run macro and temperature risk is much more costly for the agent. The size of welfare costs for temperature risk and short-run macro risk is now about 30% lower than what it was with an IES greater than one. The costs of long-run macro shocks decrease by even more and are now reduced by almost 40% compared to the benchmark case.

To quantify the long-term effects of global warming, we calculate expected losses in GDP and labor productivity 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 TFP growth, to that in an economy without temperature risk. The shock sizes are one and five standard deviations of temperature changes, i.e., 0.041°C and 0.205°C, respectively.

Table 4: The Long-run Effect of a Global Temperature Shock

Panel A: $\sum_{j=1}^{N} \Delta y_{t+j} - N \cdot \Delta y^*$ Difference in expected output growth after a shock to global temperature					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_z	−0.09	−0.27	−0.37	−0.44	−0.52
5 std. dev. σ_z	−0.44	−1.33	−1.84	−2.21	−2.60
Panel B: $\sum_{j=1}^{N} \Delta lp_{t+j} - N \cdot \Delta lp^*$ Difference in expected labor productivity growth after a shock to global temperature					
Shock size	1Y	5Y	10Y	20Y	50Y
1 std. dev. σ_z	−0.06	−0.26	−0.37	−0.45	−0.52
5 std. dev. σ_z	−0.28	−1.30	−1.85	−2.25	−2.61

Notes: This table reports the cumulative change in growth over 1, 5, 10, 20, and 50 years in percentage points after a temporary global temperature shock. The cumulative growth in an economy without such a shock is compared to that in an economy with shocks to the the global temperature z_t. Specifically, we report $\left(\sum_{j=1}^{N} \Delta y_{t+j}\right) - N \cdot \Delta y^*$ and $\left(\sum_{j=1}^{N} \Delta lp_{t+j}\right) - N \cdot \Delta lp^*$ where Δy_{t+j} (Δlp_{t+j}) is the log growth rate of total output (labor productivity), and Δy^* (Δlp^*) is the (stochastic) steady state growth rate in the economy without a shock (i.e., with $\sigma_z = 0$). For example, the entry −0.27 for a horizon of 5 years in the first row of Panel A means that cumulative growth over these 5 years has been 0.27 percentage points less than it would have been without the the global temperature shock. The amount of lost output (Panel A) and labor productivity (Panel B) growth is reported for temperature shocks amounting to one and five standard deviations, i.e., to 0.041°C and 0.205°C, respectively.

Panels A and B of Table 4 report results for output growth and labor productivity growth. One can see that a single initial temperature shock has a sizable long-run negative impact on these variables, which is clearly due to the fact that a temperature shock induces a long-lasting negative productivity shock. After one year following a one standard deviation shock, cumulative GDP and labor productivity growth decrease by nine and six basis points, and over a 50 year horizon, this shock lowers both cumulative output and labor productivity growth by 0.52 percentage points. A global temperature shock of 0.205°C exacerbates this effect — leading to a decrease in cumulative output and labor productivity growth by 0.44

and 0.28 percentage points after one year, respectively. Half a century after the shock, the decrease amounts to 2.6 percentage points each. This exercise shows that global warming adversely affects economic activity not only in the short but also in the long run by reducing growth perspectives for output and labor productivity.

The numbers reported in Table 4 may appear small at first sight, but note that they are the result of just on initial and very small shock. Given that forecasts indicate a cumulative rise in global temperature by 1 to 3 degrees Celsius over the next century, the effects of such a long-lasting sequence of upward temperature shocks can certainly be expected to be dramatic.

6 Concluding remarks

Our paper represents a first step towards the analysis of real business cycles, asset pricing, and climate change in one integrated production-based framework. Our approach is motivated by the empirical evidence that shocks to global temperature adversely impact global TFP growth. We augment the long-run risk-based production economy of Croce (2014) by time-varying temperature dynamics and wage rigidities. An important advantage of our model is its ability to simultaneously match global TFP, temperature, and asset pricing dynamics. Hence, we are able to quantify the impacts of temperature shocks on both business cycle dynamics and financial markets.

The results suggest that global warming has a profoundly negative impact on both economic activity and financial markets by lowering long-run growth prospects and asset valuations. Over a 50 year horizon, temperature risk leads to sizable losses in cumulative output and labor productivity growth. Furthermore, our model shows that the overall welfare costs of temperature risk can amount to 12% of the agent's lifetime utility. Such costs are substantially higher than those generated by other sources of risk (e.g., oil price shocks).

Our model is not fully general. For instance, it does not include features such as technological innovation (which might mitigate adverse effects of temperature changes) or social unrest (which might even exacerbate the pure growth and productivity effects we have analyzed here). Such extensions are left for future research. Still, we believe that our model allows us to address some of the issues raised by Pindyck (2013) and Revesz, Howard, Goulder, Kopp, Livermore, Oppenheimer, and Sterner (2014) concerning the structure of models designed to measure the economic costs of climate change.

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A Data

A.1 Macro Quantities

World GDP at market prices (in constant 2005 US-$), world household final consumption expenditure (in constant 2005 US-$) and world gross capital formation (in constant 2005 US-$) are used to measure output, global consumption and global investment, respectively, for the G7 countries. Per capita values are computed by dividing by total population. We use the G7 total labor force as proxy for G7 labor. All data are annual and come from the World Development Indicators (WDI) database of the World Bank. GDP data are available for the period 1960-2014 whereas data on investment and consumption ranges from 1970 to 2013. The data on the total labor force cover the period 1990-2014.

Data on Total Factor Productivity (TFP) are obtained from the latest EU KLEMS Growth and Productivity Accounts (ISIC Rev. 4) which provide TFP series at the industry-level. For our purposes, we employ the All Industries Country TPF index. Data are available for major EU economies and for the US, and freely available at `http://www.euklems.net/` for the period 1973-2009. We construct an aggregate G7 TFP index by averaging the TFP series for the following countries: Germany, Italy, Japan, United Kingdom, United States, France. Data for Canada is missing.

A.2 Asset Prices

The MSCI G7 Total Return Index (TRI) is used as the equity market return for the G7 countries. The G7 MSCI TRI (in US-$) is downloaded from Datastream and available for the period 1977-2015. As the risk-free rate we use the three-month T-bill rate that is available from the FRED database. Real rates are then obtained by adjusting for U.S. inflation using the personal consumption expenditures (PCE) deflator from the National Income and Product Accounts (NIPA) tables.

A.3 Global Temperature

The data on global surface temperature is obtained from the Climate Research Unit (University of East Anglia). More precisely, we rely on the latest global temperature dataset, `HadCRUT4`, which provides temperature anomalies across the world as well as averages for the hemispheres and the globe as a whole (Morice, Kennedy, Rayner, and Jones, 2012). Data on global temperature anomalies are freely available at `https://crudata.uea.ac.uk/cru/data/temperature/`. Global surface temperature is constructed by a weighted average of land and marine temperature anomalies on a 5° by 5° grid representing the globe. Temperature is measured by over 3,000 monthly station records and has been corrected for non-climatic influences (e.g., changes in instrumentation, changes in the environment around the station, particularly urban growth). Annual data on temperature are computed as averages of monthly observations.

A.4 Global Rainfall

Historical data on rainfall (in millimeters) have been retrieved from the Climate Change Knowledge Portal (CCKP) of the World Bank. Rainfall data are also available from the Climatic Research Unit. We collect mean monthly rainfall data for the G7 countries. The G7 rainfall series is then defined as the sum of the individual country series.

B Equilibrium

In this section, we collect all the equations that determine the symmetric equilibrium in our economy.

A symmetric equilibrium in the model is defined as an exogenous stochastic sequence, $\{\Delta a_t, x_t, z_t\}_{t=0}^{t=\infty}$, an initial condition $\{K_0\}$ for the endogenous state variable, a sequence of endogenous variables, $\{\tilde{C}_t, U_t, C_t, L_t, M_{t,t+1}, Y_t, W_t, W_t^u, I_t, D_t, V_t, q_t, G_t, R_t, R_t^f, d_t, \}_{t=0}^{t=\infty}$, and the law of motion $\{K_t\}_{t=0}^{t=\infty}$ such that

(a) the state variable $\{K_t\}_{t=0}^{t=\infty}$ satisfies its law of motion,

(b) the endogenous variables solve the firms and the consumers problems,

(c) the aggregate resource constraint is satisfied, and

(d) prices are set such that markets clear.

The equilibrium conditions of the model are summarized by the following equations:

1. Households

$$\begin{aligned}
U_t &= \left[(1-\beta)\tilde{C}_t^{1-\frac{1}{\psi}} + \beta\Big(\mathbb{E}_t[U_{t+1}^{1-\gamma}]\Big)^{\frac{1-1/\psi}{1-\gamma}}\right]^{\frac{1}{1-1/\psi}}, \\
\tilde{C}_t &= C_t^{\nu}(A_t(1-L_t))^{1-\nu}, \\
M_{t,t+1} &= \beta\Big(\frac{\tilde{C}_{t+1}}{\tilde{C}_t}\Big)^{1-\frac{1}{\psi}}\Big(\frac{C_{t+1}}{C_t}\Big)^{-1}\left(\frac{U_{t+1}^{1-\gamma}}{\mathbb{E}_t[U_{t+1}^{1-\gamma}]}\right)^{\frac{1/\psi-\gamma}{1-\gamma}}, \\
W_t^u &= \frac{1-\nu}{\nu}\Big(\frac{C_t}{1-L_t}\Big), \\
V_t &= D_t + \mathbb{E}_t[M_{t,t+1}V_{t+1}], \\
\frac{1}{R_t^f} &= \mathbb{E}_t[M_{t,t+1}].
\end{aligned}$$

2. Firms

$$
\begin{aligned}
Y_t &= K_t^{\alpha}(A_t L_t)^{1-\alpha}, \\
K_{t+1} &= (1-\delta_K)K_t + G\Big(\frac{I_t}{K_t}\Big)K_t, \\
G_t &= \frac{\alpha_1}{1-\frac{1}{\tau}}\Big(\frac{I_t}{K_t}\Big)^{1-\frac{1}{\tau}} + \alpha_2, \\
D_t &= C_t - W_t L_t, \\
q_t &= \frac{1}{G'\Big(\frac{I_t}{K_t}\Big)}, \\
1 &= \mathbb{E}_t\Big[M_{t,t+1}R_{t+1}\Big], \\
R_{t+1} &= \frac{d_{t+1}+q_{t+1}}{q_t}, \\
d_{t+1} &= \alpha\frac{Y_{t+1}}{K_{t+1}} - \frac{I_{t+1}}{K_{t+1}} + q_{t+1}G_{t+1} - \delta_K q_{t+1}, \\
W_t &= (1-\alpha)\frac{Y_t}{L_t}, \\
W_t &= (e^{\Delta a_t}W_{t-1})^{\xi}(W_t^u)^{1-\xi}.
\end{aligned}
$$

3. Market clearing condition

$$Y_t = C_t + I_t.$$

4. Evolution of the stochastic processes

$$
\begin{aligned}
\Delta a_{t+1} &= \mu_a + x_t + \sigma_a \epsilon_{a,t+1}, \\
x_{t+1} &= \rho_x x_t + \tau_z \sigma_z \epsilon_{z,t+1} + \sigma_x \epsilon_{x,t+1}, \\
z_{t+1} &= \mu_z + \rho_z(z_t - \mu_z) + \sigma_z \epsilon_{z,t+1}.
\end{aligned}
$$