Weather, Climate and the Economy: Welfare Implications of Temperature Shocks*

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Abstract

This paper examines the effects of weather shocks and climate change in the economy when rising temperatures independently affect household preferences and production technology. Direct temperature damages to the agent's preferences amplify the negative economic and welfare effects of temporary and permanent temperature increases. In our model, households value nature and dislike energy use in production. Temperature anomalies increase the disutility of energy use leading agents to reduce its use more dramatically when temperature increases. The short-run response of welfare to an unanticipated change in temperature is remarkably different when temperature directly affects preferences - welfare rises initially and then decreases as it returns to its steady state along with the temperature anomaly. Results of our analysis suggest that the consumption equivalent welfare for a 2.0°C permanent increase in temperature is approximately 3 percent of GDP.

Keywords: Business Cycles, Welfare Costs, Temperature Shocks, Climate Change.

JEL Classification: E23, E32, Q51, Q54.

1 Introduction

What are the channels through which temperature affect people's well-being? In this paper, we explore the idea that individuals might experience a disutility associated with temperature anomalies in contrast to the standard effects of climate change and weather shocks on production and growth. The novelty of our framework rests on the notion that temperature anomalies, defined here as deviations of temperature from its mean, independently affect household preferences and production technology. The independence of these two channels allow us to better characterize and quantify the effects of temperature shifts on aggregate economic activity and people's well-being. Households value nature and dislike energy use in production. If households like to consume in a pleasant environment (i.e., in an economy that uses less energy resources in production), a rise in temperature lowers consumption and energy use as temperature anomalies amplify the effect of natural resources use on the agent's utility. To the extent that negative shocks emanating from climate change as temperature anomalies affect natural resources, they could also be understood as a negative preference shock emanating from climate change, i.e., temperature anomalies cause disutility. Our exercise shows that, abstracting from the direct temperature damages to agents' utility, current economic models may have underestimated the full welfare implications of temperature shocks and climate change, potentially leading to misguided policy prescriptions.

We develop a dynamic stochastic general equilibrium (DSGE) model in which output is obtained by combining capital, labor and energy resources. The latter can be divided in two broad categories: "dirty" and "clean" energy resources, and they are imperfect substitutes in production (Golosov et al., 2014). Solar, wind, geothermal, hydropower, bioenergy and ocean power are examples of clean energy, while fossil fuels, along with nuclear energy are dirty, energy sources. Following Nordhaus (2008), we introduce a damage function which captures the negative level effect of temperature deviations on the economy's output. Along with the negative level and growth effects of temperature anomalies on production, input costs are likewise adversely affected by an increase in temperature. The representative agent in our economy experiences a disutility associated with the use of energy resources in production and temperature anomalies, as well as utility from consumption and leisure.

A key result of our exercise is that direct temperature damages to the agent's preferences amplify the effects of temperature anomalies and climate change on the economy and welfare. With environmental preferences and utility damage function, temperature anomalies increase the disutility of energy use leading agents to reduce their use more dramatically when temperature increases. Moreover, the short-run response of welfare to an unanticipated change in temperature is remarkably different when temperature directly affects preferences than otherwise. On impact, welfare rises initially and then decreases as it returns to its steady state along with the temperature anomaly (otherwise, it drops dramatically and slowly returns to the steady state level). The intuition for the initial increase in welfare is twofold: (i) the absence of the direct impact of temperature in household preferences imply that welfare is only affected by its indirect effect, through damages to production, coming from consumption, leisure, and energy use; and (ii) the temperature anomaly raises leisure and reduces the energy use as a result of lower input prices.

More specifically, our results can be summarized and grouped in terms of whether the temperature change is permanent or temporary. First, from a calibrated version of our model, we find that in the presence of a permanent temperature increase, which is essentially climate change, aggregate economic variables decrease significantly. Output decreases because of the direct effect of temperature increase through the damage function. Likewise, steady state marginal products fall as a result of a permanent increase in temperature and that output falls because of lower usage of capital, labor, and energy inputs. The decrease in output translates to lower consumption in the long run. Notwithstanding an increase in leisure and lower usage of energy inputs in the steady state, we find that welfare decreases as a result of the permanent decline in consumption. Our analysis indicates that the consumption equivalent welfare for a 2°C permanent increase in temperature (the percentage increase in consumption, relative to the GDP, that an individual would require to be as well off as in the benchmark case) is around 3 percent of GDP. Furthermore, our model predicts that GDP decreases by 1.48% for this magnitude of temperature change. To put our results into perspective, consider the U.S. economy with a GDP of $18.57 trillion (2016). Our analysis suggests that the consumption equivalent welfare for the U.S. is $557 billion for a 2°C permanent increase in temperature.[1]

Second, we find that for an unanticipated temporary increase in temperature (a weather shock), consumption and hours worked (leisure) fall (increase) instantaneously. The decrease in labor supply, energy, and capital is due to the reduction in their respective input prices. On impact, welfare decreases mainly as a result of lower consumption. As temperature reverts back to its previous steady state value, input prices increase along with the demand for factors of production (i.e., capital, labor, energy). Output and consumption rises gradually until they return to their steady states. Remarkably, the dynamic response of welfare to an unanticipated temporary increase in temperature does not vary as much for the case of with and without environmental preferences or altering the channels through which temperature can affect the economy. We also studied an interesting case where temperature influence total factor productivity (TFP) directly. Our results indicate that the dynamic response of welfare is rather persistent for this particular case given that the temperature shock assumes the persistence properties of the TFP shock. We also conducted additional experiments to test the robustness of our results. Precisely, we experimented on using reasonable ranges of parameter values and transforming the weather shock to generate welfare improvements. We find that changing the parameter values failed to overturn the qualitative features of our benchmark results.

There is considerable evidence which demonstrate that the Earth's climate is changing. Our current understanding of climate change is largely the result of the Intergovernmental Panel on Climate Change (IPCC). According to the IPCC (2001), the global average surface temperature has increased over the 20th century by about 0.6 degrees Celsius and that it is projected to increase as much as 5.8°C by the year 2100. It is believed that such temperature anomalies can bring about an increase in frequency of extreme weather events, such as monsoon rains and hurricanes, and a rise in the sea-level. According to the The Economist (2017), since 1970, the number of weather-related disasters worldwide has more than quadrupled to around 400 a year. These consequences, in turn, produce short- and long-term impacts on the economy and people's welfare. Applying vector autoregression techniques to U.S. data, we verify

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[1] Bansal and Ochoa (2011) find that the temperature related utility-costs are about 0.78% of consumption, and the total dollar costs of completely insuring against temperature variation are about 2.46% of World GDP.

that a one-degree Celsius increase in temperature produce adverse effects to growth in GDP, aggregate consumption, aggregate investment, and labor supply.

The specification of economic damages due to global temperature changes have been modeled in a variety of ways. Some authors (notably Nordhaus (1982, 1991)) have added temperature effects to production, while others have included temperature as an argument in the utility function (e.g., Tahvonen and Kuuluvainen (1991), Stollery (1998), Heal and Park (2013)). In principle, increases in global temperature, i.e., temperature anomalies, can potentially affect both the economy's production and the agents' utility, features that are captured in our model. In this sense, we contribute to the literature by recognizing the importance of climate change in individual preferences.

This paper builds on the growing literature, which applies macroeconomic models to study climate policy (see, for instance, Fried (2018), Donadelli et al. (2017), Golosov et al. (2014), Krusell and Smith (2009), Hassler and Krusell (2012)). However, although there is a large literature on environmental preferences (e.g., Kama (2001); Belfiori (2017)), and on the fact that temperature can be related to individual preferences (for instance, Fankhauser and Tol (2005)), these important features and their interactions are yet to be studied in the context of a DSGE framework.[2] By jointly considering environmental preferences and the direct impact of temperature in the utility, our approach is a departure from the existing literature (Nordhaus and Moffat, 2017; Nordhaus, 2008; Tol, 2009; Fankhauser and Tol, 2005; Dell et al., 2014; Gallic and Vermandel, 2016; Donadelli et al., 2017; Lintunen and Kuusela, 2018).

Three papers are closely related to ours and we discuss them in detail here.[3] Donadelli et al. (2017) developed a DSGE model to quantify the effects of temperature changes on business cycles. Precisely, they augment the production with temperature dynamics that are coupled with TFP such that rising temperatures will produce a negative impact on long-run productivity growth: "over a 50-year horizon, a one standard deviation temperature shock lowers both cumulative output and labor productivity growth by 1.4 percentage points." They also found that non-negligible welfare costs due to rising temperatures amount to 18.4% of the agent's lifetime utility. Gallic and Vermandel (2016) studied the impact of temperature changes in the agriculture sector. They found that weather shocks act in a similar fashion to a negative supply shock characterized by declining output and rising relative prices in the agricultural sector. Golosov et al. (2014) developed a model with an externality (climate change) through the use of fossil energy. Their central result is "a simple formula for the marginal externality damage of emissions (or, equivalently, for the optimal carbon tax)". Our study distinguishes itself from these three papers in the following respects. First, unlike the three aforementioned papers, our DSGE model considers the adverse effects of temperature on individual preferences. The presence of temperature in the utility function makes allocation choices and economic dynamics richer but more complicated. Second, in contrast to Gallic and

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[2] Fankhauser and Tol (2005) have suggested that non-market effects of temperature anomalies such as the "amenity value of climate and the effect on recreational and environmental assets". Although the economy-wide impacts of climate change have been widely studied, little is still known on the dynamic effects of variable weather phenomena on agents that care about nature and are affected by temperature anomalies. Short and long term welfare implications of these events are yet to be better understood.

[3] There are other papers that examine the link between macroeconomic variables and the environment using DSGE models in an RBC framework (Fischer and Springborn, 2011; Dissou and Karnizova, 2016) or a New Keynesian setup (Annicchiarico and Dio, 2015). While these studies focus on optimal environmental policies, our study focuses on the implications of climate change (long-run) and weather shocks (short-run) on the aggregate economy.

Vermandel (2016) and Golosov et al. (2014), our study examines the welfare consequences of climate change or the long-run permanent change in temperature. We also provided estimates of consumption equivalents when temperatures increase permanently. To the best of our knowledge, our study is the first to characterize and quantify the welfare impacts of temperature shocks and climate change by jointly considering environmental preferences and temperature in utility.

Our study relates to the growing literature about the effects temperature shifts in the economy - also called the 'New Climate-Economy Literature'. Studies in this new strand of literature found overwhelming evidence that increases in temperature could produce dramatic and significant effects on aggregate economic activity (Nordhaus and Moffat, 2017; Nordhaus, 2008; Tol, 2009; Fankhauser and Tol, 2005). Scholars found that hotter temperatures have adverse effects in agricultural production (Schlenker and Roberts, 2009), labor productivity (de Montesquieu, 1748; Seppänen et al., 2006; Heal et al., 2017), and industrial production (Hsiang, 2010). Notably, this new strand in the literature identified several channels through which temperature anomalies can affect the aggregate production function. First, higher temperatures can potentially lead to high evaporation and unstable supply of water thus reducing agricultural output (Schlenker and Roberts, 2009) and productivity (Mendelsohn et al., 1994). Second, weather fluctuations lead to substantial changes in labor supply. For instance, Graff-Zivin and Neidell (2014) found that temperature increases reduce hours worked in industries with high climate exposure. Third, recent empirical work finds that weather shocks have significant negative effects on industrial and services output (Hsiang, 2010; Dell et al., 2014). Fourth, extreme heat raises mortality rates and have negative effects on the health of the population (Deschenes and Greenstone, 2007). As explained by Dell et al. (2014), these four channels are non-exhaustive as there are other important channels through which aggregate output can be influenced by climate change. Given their effects on output, temperature anomalies ultimately produce adverse effects on welfare and the well-being of the population.

Finally, although individual preferences with respect to the environment are unobservable, scholars have used public opinion polls and surveys to gauge preferences toward the environment. Public opinion polls have shown that the majority of the population acknowledges the existence of climate change and that it constitutes a very serious problem (Borick et al., 2011). According to the Pew Global Attitudes Survey, there is a growing global concern about climate change and that respondents in nations surveyed cite climate change as their biggest worry, making it the most widespread concern of any issue included in the survey. In the same survey, respondents indicated that droughts or water shortages, severe weather, long periods of unusually hot weather, and rising sea levels are effects of global warming that concerns them the most (Pew Research Center, 2015). Apart from climate change, there is also evidence that the public supports conservation of natural resources. A recent survey found that, when people have to choose, environmental protection is prioritized over economic growth in most surveys and countries (Drews et al., 2018). Moreover, opinion polls strongly suggest that the public cares deeply about the environment and that the frequency of extreme weather events have led to increased recognition of the threat of climate change (Brulle et al., 2012). Opinion polls also found that the public attach a great value to the environment and are increasingly aware of the role that the environment plays in their live (Eurobarometer, 2008). Based on these empirical evidences, we believe therefore that environmental preferences has to be included in the analysis of economic effects of climate change.

The remainder of this study is organized as follows. Section 2 provides empirical evidence on the effects of temperature changes on macroeconomic variables. Section 3 describes the model. Section 4 presents the results from a calibrated version of our model where we explore the quantitative implications of weather (temporary) shocks and climate change (permanent shock) on aggregate economic activity and welfare. Section 5 concludes.

2 Empirical Analysis

In this section, we present our empirical findings to motivate intuition and provide empirical support for our model. We conduct our empirical analysis by examining the data on U.S. temperature dynamics and analyze their effects on macroeconomic variables. Our model is consistent not only with business cycle stylized facts, but also with empirical evidence pointing towards the economic implications of weather and climate change.

The U.S. temperature, expressed in degrees Celsius, were collected from the NOAA National Center for Environmental information. Temperature data used in the empirical analysis were annual from 1950 to 2015. As shown in Figure 1, the U.S. average temperature has increased since record keeping began in 1895 and that the most of this increase has occurred since about 1970. Figure 1 also demonstrate that temperature exhibit frequent fluctuations from its trend. We find that the average deviation in U.S. temperature is 0.018 degrees Celsius. Moreover, our calculations indicate that the volatility of temperature, measured by the standard deviation of temperature deviations from its trend, is at 0.94 (σ_T). To put these results to perspective, consider the volatility of U.S. GDP. We find that U.S. GDP volatility is more than twice greater than the volatility of temperature. We also find that the deviations of temperature are not as persistent relative to macroeconomic variables, such as GDP or TFP.

Recent empirical studies found that increases in temperature produce adverse effects on real economic activity (Bansal and Ochoa, 2011; Cai et al., 2015; Colacito et al., 2018; Dell et al., 2012; Du et al., 2017). We present evidence of the impact of rising temperatures on the following macroeconomic variables: output growth, consumption growth, investment growth, and labor supply growth. All of the U.S. macroeconomic variables are obtained from the Bureau of Economic Analysis (BEA). Figure 2 shows the impulse-response function of the macroeconomic variables to a one-standard deviation shock in temperature. The impulse response is derived from the Cholesky orthogonalization of a bivariate VAR model with one lag in which the temperature shock is ordered first. Consistent with existing evidence, our results suggest that a temporary temperature shock reduces growth in output, consumption, investment, and labor supply. On impact, we observe that output growth, consumption, and labor supply growth decreases by around 3 percentage points, while investment decreases by 1 percentage point. The observed negative effect exhibit persistence, lasting for more than five years and is statistically significant at the 5% level. Taken together, we find that the lagged effect of a temperature shock on the economic variables does not affect all variables homogeneously and, thus, propagates only gradually across the economy.

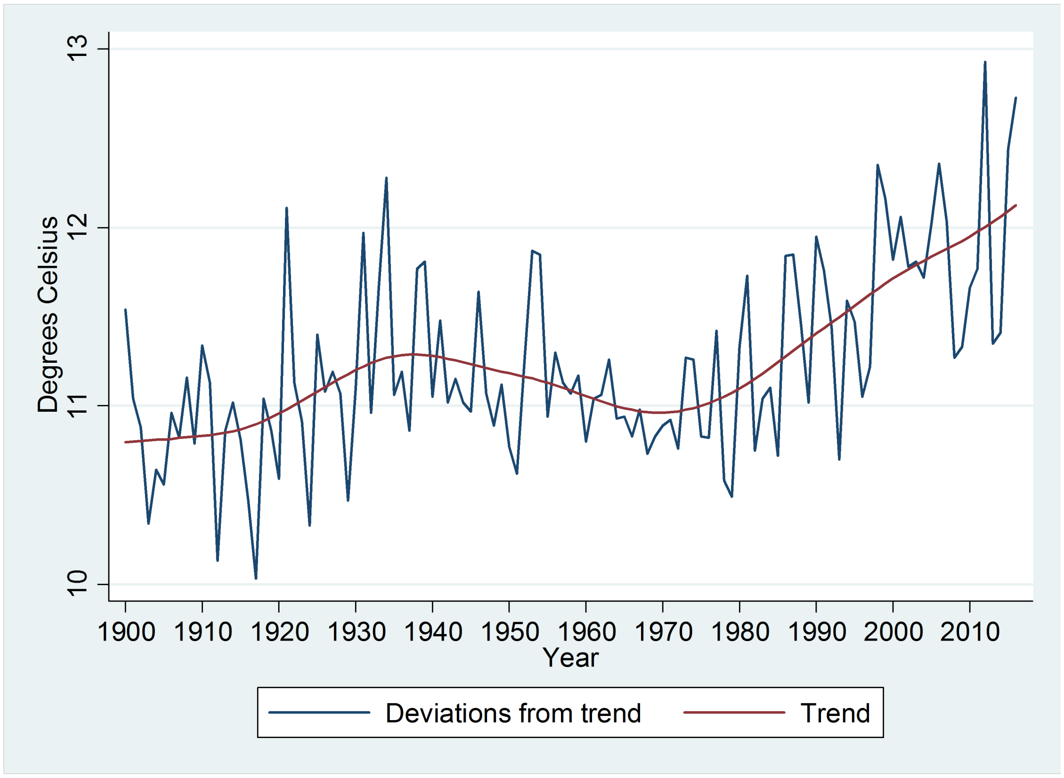

Figure 1: U.S. historical temperature data, 1896-2017.

3 The Economy and the Climate

3.1 Technology, Energy Inputs and Firms

A final good output Y_t is described by an aggregate production function $F(K_t, A_tL_t, E_t)$ which includes the standard inputs, capital (K_t) and labor (L_t), along with $E_t = (E_{1t}, E_{2t})$ denoting a vector of energy inputs used in production at time t, and a stochastic productivity shock A_t.

The production technology is given by

$$Y_t = D^Y(T_t)\, F(K_t, A_tL_t, E_t). \tag{1}$$

Following (Golosov et al., 2014), we assume that the energy input E_t is a composite of two energy sources. Think of E_{1t} as a “dirty” energy source generated from exhaustible (non-renewable) natural resources, for instance, oil and coal. On the other hand, E_{2t} represents “clean” or “green” energy.

A damage function is introduced in the spirit of integrated assessment models (IAMs) pioneered by Nordhaus (1991). We follow Nordhaus (2008), among others, and assume that damages due to climate change, denoted by $D^Y(T_t)$, are multiplicative and captures the mapping from climate (usually represented by the temperature anomalies, defined here as the deviations T_t from the global mean temperature) to economic damages measured as a percent of final good output. In Section 4.3, we consider the effects of temperature anomalies on the growth rate of TFP as in Donadelli et al. (2017).

The capital stock and the energy inputs time-varying productivity (or efficiency) evolve according to,

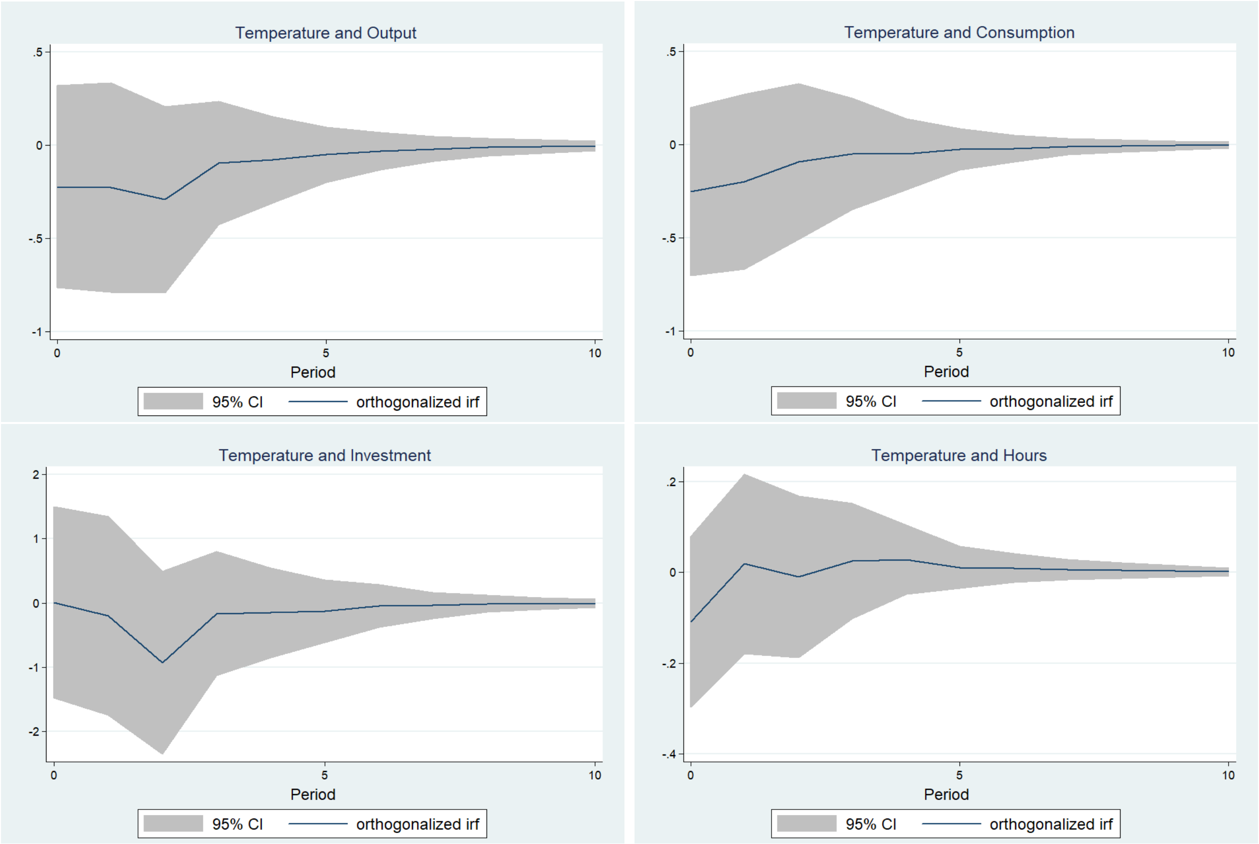

Figure 2: Cholesky orthogonalized impulse response of macroeconomic variables to temperature.

respectively,

$$\begin{aligned} K_{t+1} &= I_t^K + (1-\delta_K)K_t + G\left(\frac{I_t^K}{K_t}\right)K_t && (2) \\ E_{it+1} &= I_t^i + (1-\delta_i)E_{it}, && (3) \end{aligned}$$

where $\delta_K \in (0,1)$ is the physical capital depreciation rate and $\delta_i \in (0,1)$, $i = \{1,2\}$, represents the rate of decline in energy efficiency. The physical capital law of motion, equation (2), features a convex investment adjustment cost G$(\cdot)$. From a firm perspective, investments on energy efficiency, I_t^i, can be interpreted as spending, for instance, on solar panels, new machinery, fertilizers to maintain the productivity of the field and factories. While investments in energy efficiency may be considered as investments that transform into physical capital, we assume that these investments are distinct from each other.[4]

Perfect competition among firms and constant returns to scale in the production function implies zero profits for all firms and an indeterminate size distribution of firms. Thus there is no need to specify the ownership structure of firms in the household sector, and without loss of generality we can assume the existence of a single representative firm. This representative firm rents physical capital, buys dirty and clean energy inputs, and hires workers on competitive spot markets at prices r_t (the return to physical

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[4] Our approach to disentangle investments in physical capital and those investments in energy efficiency have been used in the literature. For instance, Gallic and Vermandel (2016) studied the effects of climate change in a model with investments in physical capital and investments in agricultural efficiency.

capital), p_{it} (the price of energy of type $i = \{1, 2\}$), and w_t (the real wage). Final-good firm's profit maximization implies the following conditions

$$\begin{aligned} r_t &= D^Y(T_t)\, F_K(t) && (4)\\ p_{1t} &= D^Y(T_t)\, F_E(t) E_{E_1}(t) && (5)\\ p_{2t} &= D^Y(T_t)\, F_E(t) E_{E_2}(t) && (6)\\ w_t &= D^Y(T_t)\, A_t F_L(t) && (7) \end{aligned}$$

Notice that these conditions are otherwise standard, except for the damages to production due to temperature anomalies, $D^Y(T_t)$.

3.2 Household Preferences and Equilibrium Conditions

We consider an infinitely lived representative household who derives utility from consumption C_t and leisure $H_t = 1 - L_t$. The agent also values nature quality captured here by the disutility associated with the use of energy inputs $E_t = (E_{1t}, E_{2t})$ (a proxy for natural resources) in production.

In line with recent literature, we also assume that temperature anomalies affect agent's utility. Several studies have put forward evidence that people not only care about nature, but also that temperature anomalies affect how they make choices such as time allocation decisions (for instance, see Graff-Zivin and Neidell (2014)). As a benchmark we assume that temperature anomalies directly affect the household welfare through a multiplicative utility damage function $D^U(T_t)$. This damage function captures the direct effect of a given temperature anomaly T_t, at time t, on agents' preferences. One can also interpret this damage function as a direct measure of climate change disutility.

The representative household maximizes

$$\mathbb{E}_t \sum_{t=0}^{\infty} \beta^t D^U(T_t)\, U(C_t, H_t, E_t), \tag{8}$$

subject to the following sequence of budget constraints

$$C_t + I_t^K + I_t^1 + I_t^2 = w_t L_t + r_t K_t + p_{1t} E_{1t} + p_{2t} E_{2t} \tag{9}$$

and the laws of motion, equations (2) and (3), where U is a standard concave period utility function, $\mathbb{E}$ denotes the expectation operator, $\beta \in (0, 1)$ is the discount factor.

From the agent's first-order conditions with respect to $C_t, L_t, K_{t+1}, E_{1t+1}, E_{2t+1}, I_t^K, I_t^1, I_t^2$ we obtain the following competitive equilibrium conditions:

$$\begin{aligned} U_C(t) w_t &= U_H(t) && (10)\\ \frac{D^U(T_t)\, U_C(t)}{1 - g^K(t)} &= \beta\, \mathbb{E}_t\, D^U(T_{t+1})\, U_C(t+1) \left(r_{t+1} + \frac{(1-\delta_K) + \Gamma_{t+1}^K}{1 - g^K(t+1)} \right) && (11)\\ D^U(T_t)\, U_C(t) &= \beta\, \mathbb{E}_t\, D^U(T_{t+1})\, U_C(t+1) \left(p_{1t+1} + (1-\delta_1) + U_E(t+1) E_{E_1}(t+1)\right) && (12)\\ D^U(T_t)\, U_C(t) &= \beta\, \mathbb{E}_t\, D^U(T_{t+1})\, U_C(t+1) \left(p_{2t+1} + (1-\delta_2) + U_E(t+1) E_{E_2}(t+1)\right) && (13) \end{aligned}$$

where $g^K(\cdot)$ is the derivative of the adjustment cost function $G(\cdot)$ with respect to investment I^K, $\Gamma_{t+1}^K = g^K(t+1)\,I_{t+1}^K - G(t+1)\,K_{t+1}$, and r_t^K, $p_{1,t}$, $p_{2,t}$ and w_t are given by (4) - (7), respectively.

At first glance, the household equilibrium conditions, equations (10) - (13), seem fairly standard. However, when climate change (temperature anomalies) affects the agent's utility and production through utility- and production-damage functions, and consequently through the prices of the factors of production and marginal utility, it affects agent's optimal allocations decisions in non-trivial and interesting ways. For example, equation (10) expresses the marginal rate of substitution between consumption and the labor-leisure choice. Notice that while this intratemporal choice is not affected by temperature anomalies directly (the term $D^U(T)$ cancels out), to the extent that the marginal productivity of labor (w_t) falls when temperature increases, climate change affects the agent's choice of consumption and leisure.

The household intertemporal choices, on the other hand, are affected by the impact of temperature anomalies on production and utility. Consider, for instance, the agent's choice of "clean" energy E_{2t}, equation (13). This intertemporal choice takes into account the marginal utility of more consumption in the future - more resources translate into more output and consumption - but also the disutilty the agent experiences of more energy (natural resources) being used in production. In this case, an increase in temperature affects the household choices and trade-off not only through its effect on the input price p_2 (an increase in temperature should lower gross returns which leads to lower utilization of this input) but also via its utility damage of the current marginal utility of consumption $D^U(T_t)\,U_C(t)$ vis-à-vis the future marginal utility of consumption $D^U(T_{t+1})\,U_C(t+1)$. Similarly for the household intertemporal choice of "dirty" energy, equation (12). Finally, it is important to point out a key distiction between the optimal choices of physical capital (K) and energy inputs (E_1, E_2). Because our representative agent exhibits environmental preferences, temperature anomalies have an additional impact on the intertemporal choice of energy inputs, i.e., the future disutility of energy use - the last terms of equations (12)-(13) - which is not present in the physical capital optimal decision, equation (11).

3.3 Aggregate Resource Constraint

We abstract from government, international trade, and population growth. The economy's resource constraint in period t is then

$$Y_t \;=\; C_t + I_t^K + I_t^1 + I_t^2 \tag{14}$$

Since there are no externalities and other market imperfections, the competitive equilibrium in this economy can be calculated as the solution to the appropriate social planning problem. Given A_0, T_0, K_0, E_{10}, and E_{20}, the social planner maximizes the expected lifetime utility of the representative agent, equation (8), by choosing the optimal sequences $\{C_t, K_{t+1}, E_{1t+1}, E_{2t+1}, , L_t, Y_t\}_{t=0}^{\infty}$, subject to the resource constraint, equation (14), law of motion equations (2)-(3), and the production technology, equation (1).

4 Quantitative Analysis

We now describe the results from a calibrated version of our model. Since we cannot analytically find the equilibrium solution, log-linearized approximations to the equilibrium decision rules around the steady state are therefore computed for this economy. With this numerical solution, we will explore the economic implications of temperature anomalies, focusing in particular on how temporary (weather) and permanent (climate) temperature shocks affect the model's endogenous outcomes such as agent's allocations and welfare.

4.1 Model Parametrization and Calibration

In this section, we present our model parametrization and discuss how the calibration choices were made. Functional forms for production $F(K, AL, E)$ and utility $U(C, H, E)$ functions, and energy composite $E = (E_1, E_2)$ are required. We will also need to specify the functional form of the utility- and production-damage functions, $D^U(T)$ and $D^Y(T)$, respectively. In the discussion that follows, we drop the t subscript for convenience and wherever it would not lead to confusion.

As a benchmark, we set the discount factor $\beta = 0.985$, which is consistent with the discount rate of 1.5% per year according to Nordhaus and Sztorc (2013). We need to calibrate the following sets of parameters: those involving the output and utility damage functions, technology and preferences parameters, those related to energy inputs and energy composite and, finally, technology and temperature stochastic shock parameters. All parameters are summarized in Table I.

We assume a Cobb-Douglas specification for the final good:

$$Y = D^Y(T) K^{\alpha} (AL)^{1-\alpha-\nu} E^{\nu}, \tag{15}$$

and we use the standard value of 0.3 for α, and assume ν equals 0.04 (Golosov et al., 2014), which implies that the labor share in production is 0.66.

Energy inputs are imperfect substitutes in production and the energy composite E is defined as

$$E = \left[\kappa_1 E_1^{\rho} + \kappa_2 E_2^{\rho}\right]^{\frac{1}{\rho}}, \tag{16}$$

where the ρ determines the elasticity of substitution between dirty and clean energy, κ measures the relative energy efficiency of the different energy sources, and $\kappa_1 + \kappa_2 = 1$. To calibrate κ_1 and κ_2, we first restrict the dirty energy input to oil only and we use the relative prices of oil to renewable clean energy, given by equations (5) and (6), i.e., $(p_1/p_2) = (\kappa_1/\kappa_2)(E_1/E_2)^{\rho-1}$. We follow Golosov et al. (2014) and take unity as a reasonable value of the current relative price between green energy and oil. Next we set κ_1 and κ_2 to 0.58996 and 0.41004 such that the total energy input E_t used in production is the same as in their study.

According to data on global energy consumption from IEA (2010), the primary global energy demand in 2008 was 4.059 Gtoe (gigaton of oil equivalents). Setting the carbon content in crude oil to 846 KgC/ton, we express the amount of oil in carbon units by multiplying its energy demand by its carbon content of 84.6%, which implies an amount $E_1 = 3.43$ of oil extracted. Assuming a benchmark value for the elasticity of substitution parameter between dirty (oil) and green energy ρ equals to -0.058, which implies an elasticity of substitution equals to 0.95 (Golosov et al. (2014) and Stern (2012)), we obtain a value for the amount of clean energy $E_2 = 2.432$. The rate of decline in energy efficiency for both energy inputs, $\delta_i \in (0, 1)$, $i = \{1, 2\}$, is set to 0.03 based on the Bureau of Economic Analysis Depreciation

Table I: Benchmark Model Parameters.

Parameter	Description	Source	Value
Preferences			
β	Discount factor	1	0.9850
ϕ_H	Weight on leisure	5	1.1302
ϕ_E	Weight on natural resources	5	0.0387
η	Elasticity of labor supply	5	2.00
Production and Energy Inputs			
α	Capital share of output	5	0.30
ν	Energy share of output	5	0.04
δ	Physical capital depreciation rate	4	0.10
δ_1	Rate of decline in "clean" energy efficiency	2	0.030
δ_2	Rate of decline in "dirty" energy efficiency	2	0.030
κ_1	Relative dirty energy efficiency	5	0.58996
κ_2	Relative clean energy efficiency	5	0.41004
ρ	Elasticity of substitution: dirty and clean energy	3	-0.058
Damage Functions			
θ_Y	Damage function coefficient - Output	5	0.0026
θ_U	Damage function coefficient - Utility	5	0.0024
$\overline{T}$	Long-run mean of temperature deviation (anomaly)	1	$2^o C$
Technology and Temperature Shocks			
$\overline{A}$	Long-run (steady state) TFP	1	1.00
φ_A	Long-run TFP shock persistence	4	0.95
σ_A	Volatility of long-run shocks to TFP	4	0.47
φ_T	Long-run temperature anomaly shock persistence	5	0.46
σ_T	Volatility of long-run shocks to temperature anomaly	5	0.94

Note: The parameter values were sourced as follows: 1: Nordhaus (2008); 2: BEA (2007); 3: Stern (2012); 4: Prescott (1986); 5: calibrated by authors.

Estimates (BEA, 2007).

Capital is assumed to depreciate at the rate of 10 percent per year, hence $\delta = 0.10$. We assume that the capital adjustment function takes the following functional form $G\left(I_t^K/K_t\right) = (\phi_K/2)\left(\left(I_t^K/K_t\right) - \delta\right)^2$, following the form set by Hayashi (1982), and we calibrate ϕ_K such that equilibrium conditions are satisfied in the steady state.

Regarding the functional form of temperature damages to the economy's output, we use Nordhaus's damage function of global temperature, specified as

$$D^Y(T) = \frac{1}{1 + \theta_Y T^2}, \tag{17}$$

where T is the mean global increase in temperature above the pre-industrial level. The benchmark temperature anomaly is set to 2.0° Celsius ($\overline{T} = 2.0$), which implies a global mean temperature increase of equivalent magnitude. In our model, we set $\theta_Y = 0.0028388$ so that this temperature anomaly produces the corresponding steady state damage to GDP of about 1.0%. This damage in GDP is consistent with Nordhaus (2008)'s Figure 3-3, p. 51, as well as estimates of climate damages reviewed in Tol (2009) (see also Nordhaus and Sztorc (2013) and Dell et al. (2014). Golosov et al. (2014) assumes the same functional form and their value for the damage function parameter ($\theta_Y = 0.0026041$) is very close to ours.

The utility function of the representative agent is assumed as follows

$$U = D^U(T)\left(\log(C) + \phi_H \frac{(1-L)^{1-\eta}}{1-\eta} - \phi_E E_t\right), \tag{18}$$

where the energy composite is defined as in equation (16). The individual labor supply elasticity is assumed equal to $\eta^{-1}(1/L^* - 1)$, where L^* is the steady state value of the labor input (i.e., the average time spent working $L^* = 0.33$). For calibration purposes, we assume a unit elasticity of labor supply, which implies $\eta = 2$. In order to calibrate the relative weight of leisure in the utility function parameter ϕ_H, we use the intratemporal equilibrium condition, equation (10), and the steady state allocations for consumption, labor and the wage rate, and we obtain $\phi_H = 1.1302$. Under our assumption that the current relative price between green energy and oil is equal to one, we set $\phi_E = 0.0387$, in accordance with the equilibrium conditions, equations (12)-(13) and equations (5)-(6).

It is more difficult to find estimates for temperature damages to the utility derived from consumption, leisure and natural resources. To proceed, we first assume, as a benchmark, that the utility damage function has a similar functional form as the output damage function, equation (17), i.e., $D^U(T) = \left(1 + \theta_U T^2\right)$, which is consistent with our functional form for the utility function, equation (18). To calibrate the parameter θ_U, we use evidence from Graff-Zivin and Neidell (2014) of the impacts of temperature on individual's allocation of time. They find evidence of a moderate decline in aggregate time allocated to labor at high temperatures when daily maximum temperatures increase beyond 85°F (29°C) - time that is most reallocated to indoor leisure. While the impact of higher temperatures on outside leisure is not significant, at daily maximum temperatures over 100°F (38°C), Graff-Zivin and Neidell (2014) estimate a statistically significant increase in indoor leisure of 27 minutes relative to the benchmark 76-80°F (24-27°C). In our model, their estimates imply that the representative agent reduces her labor supply from $L^* = 0.33$ to $\hat{L} = 0.30$, with leisure increasing from $H^* = 0.67$ to $\hat{H} = 0.70$ (assuming that people have 16 hours/day at their disposal not spent sleeping or attending to personal care, i.e., to spend on leisure or work). Since at high temperatures workers appear to substitute their time allocated to labor for (indoor) leisure, we find the optimal allocations (in particular, consumption and energy inputs) consistent with Graff-Zivin and Neidell (2014) values for labor $\hat{L} = 0.30$. Then, we set θ_U such that $\left(1 + \theta_U T^2\right)^{-1} U(C^*, L^*, E^*) = U\left(\hat{C}, \hat{L}, \hat{E}\right)$. This yields $\theta_U = 0.0024$ as our benchmark.

The remaining parameters are those that describe the stochastic processes for the technology and temperature shocks. As a benchmark we assume that temperature anomalies have no impact on the economy's TFP. We revisit this assumption in Section 4.3. The productivity shock A_t evolves as an AR(1) process:

$$A_t = (1 - \varphi_A)\overline{A} + \varphi_A A_{t-1} + \epsilon^A_{t-1}, \tag{19}$$

where $0 < \varphi_A < 1$, $\overline{A}$ is the TFP steady state value, normalize to 1, and $\epsilon^A \sim (0, \sigma_A^2)$ is an independent and identically distributed random variable. Estimates for technological shocks parameters are provided by (Prescott, 1986) where the long-run TFP shock persistence is $\varphi_A = 0.95$ and the volatility of long-run shocks to TFP (σ_A) is set to 0.47.

Temperature anomalies follow the stationary stochastic process

$$T_t = (1 - \varphi_T)\overline{T} + \varphi_T T_{t-1} + \epsilon_{t-1}^T, \tag{20}$$

The autocorrelation coefficient in the stochastic process for the temperature anomaly, which measures the persistence of the temperature shock, is set to $\varphi_T = 0.46$. Moreover, the data reveal that temperature anomaly series is volatile (Bansal and Ochoa, 2011; Donadelli et al., 2017). We therefore set σ_T equal to 0.94, so that the temperature anomaly in the model have the same volatility as observed in the data.

Table II displays a number statistics of interest observed in the data and implied by our benchmark model. In all moments, we compute the equilibrium dynamics by solving a log-linear approximation to the set of equilibrium conditions. Although the focus of the paper is not to assess the models' abilities to match the data, as a reference we include in column (1) the observed moments using the U.S. data. Generally, as shown in column (2), the business cycles properties of our economy are consistent and qualitatively similar to those observed in standard real business cycle models. The model also produces volatilities that closely matches what is observed in the data. Our benchmark model predicts the following ranking of volatilities, in ascending order: investment, consumption and output. It underpredicts, though, the volatility of investment which is similar to Donadelli et al. (2017).

Our model closely matches the shares of aggregate consumption and investment to output, as well as the correlations between these aggregates and output. In terms of the temperature variables, our model is able to successfully match their moments. It overpredicts the correlation between output and temperature, although it correctly predicts the direction of the relationship. Summarized in columns (3) and (4) are the business cycle characteristics of our model when $\theta_Y = 0$ (utility damage only) and $\theta_U = 0$ (production damage only), respectively. The case where $\theta_Y = 0$ implies that temperature can affect the economy only through damages to the agents' utility. Conversely, the case $\theta_U = 0$ captures the scenario where temperature affect the economy only through the production function.

4.2 The Effects of Weather Shocks and Climate Change

In this section we present numerical exercises to analyze the effects of temperature anomalies in our benchmark economy, i.e., temperature anomalies damage output and agents' utility ($\theta_Y \neq 0$, $\theta_U \neq 0$, respectively) and people value energy use ($\phi_E \neq 0$). We first consider temporary (weather) and then permanent (climate) temperature shocks to understand how the economy is affected in the short versus long run and to study the implications of such temperature anomalies for the agents' welfare.

4.2.1 Weather Shocks: Temporary Effects of Changes in Temperature

The results for the temporary effects of temperature anomalies are obtained by computing the impulse response functions (IRFs) following a 2°C unanticipated increase in temperature. The IRFs for the main variables are summarized in Figure 3. The effects of a temporary change in temperature in the economy can be characterized from two channels. First, temperature affects the economy through the production

Table II: Model versus data.

	US data (1)	Benchmark model (2)	Utility damage only (3)	Production damage only (4)
θ_Y		Yes	No	Yes
θ_U		Yes	Yes	No
Temperature				
T	0.02	0.02	0.02	0.02
$\sigma(T)$	0.94	0.94	0.95	0.95
$corr(Y,T)$	-0.02	-0.00	0.00	0.00
$corr(C,T)$	-0.01	-0.00	0.00	-0.00
$corr(I,T)$	0.00	-0.00	0.00	-0.01
$corr(L,T)$	0.02	-0.01	0.00	-0.01
Macroeconomic variables				
C/Y	0.66	0.80	0.80	0.80
I/Y	0.25	0.20	0.20	0.20
$\sigma(Y)$	1.92	1.92	1.93	1.93
$\sigma(C)$	1.36	1.22	1.22	1.22
$\sigma(I)$	4.90	0.84	0.84	0.84
$corr(Y,C)$	0.90	0.93	0.93	0.93
$corr(Y,I)$	0.93	0.87	0.87	0.87
$corr(Y,L)$	0.83	0.68	0.68	0.68

function. Instantaneously, following an unanticipated temporary rise in temperature, the damage to output rises thereby leading to a decline in factor prices (i.e., wage, rental rate, and price of energy). The dynamic response of labor supply, the energy composite, and physical capital is to decrease as a result of the reduction in input prices. The reduction in input demand leads to lower production and, consequently, output. Second, given that households in our model care about energy use and climate, temperature affects the economy through household preferences. An unanticipated increase in temperature raises the damage to utility thereby directly affecting (negatively) consumption and the energy composite. Consumption falls as a result of a decrease in marginal utility of consumption following an increase in temperature. Similarly, the disutilities of labor and energy rises which leads to a decrease in labor supply.

4.2.2 Climate Change: Permanent Effects of Changes in Temperature

We now turn our attention to permanent changes in temperature to study its long term effects on output (GDP) and agents' welfare. To analyze the welfare consequences of temperature anomalies we compute two measures of welfare losses, namely, the change in welfare due to temperature increase as a percentage of the benchmark welfare (welfare loss) and the consumption equivalent (the percentage increase in consumption, relative to the GDP, that an individual would require to be as well off as in the benchmark case). Table III reports the effects of a permanent increase in the global mean temperature

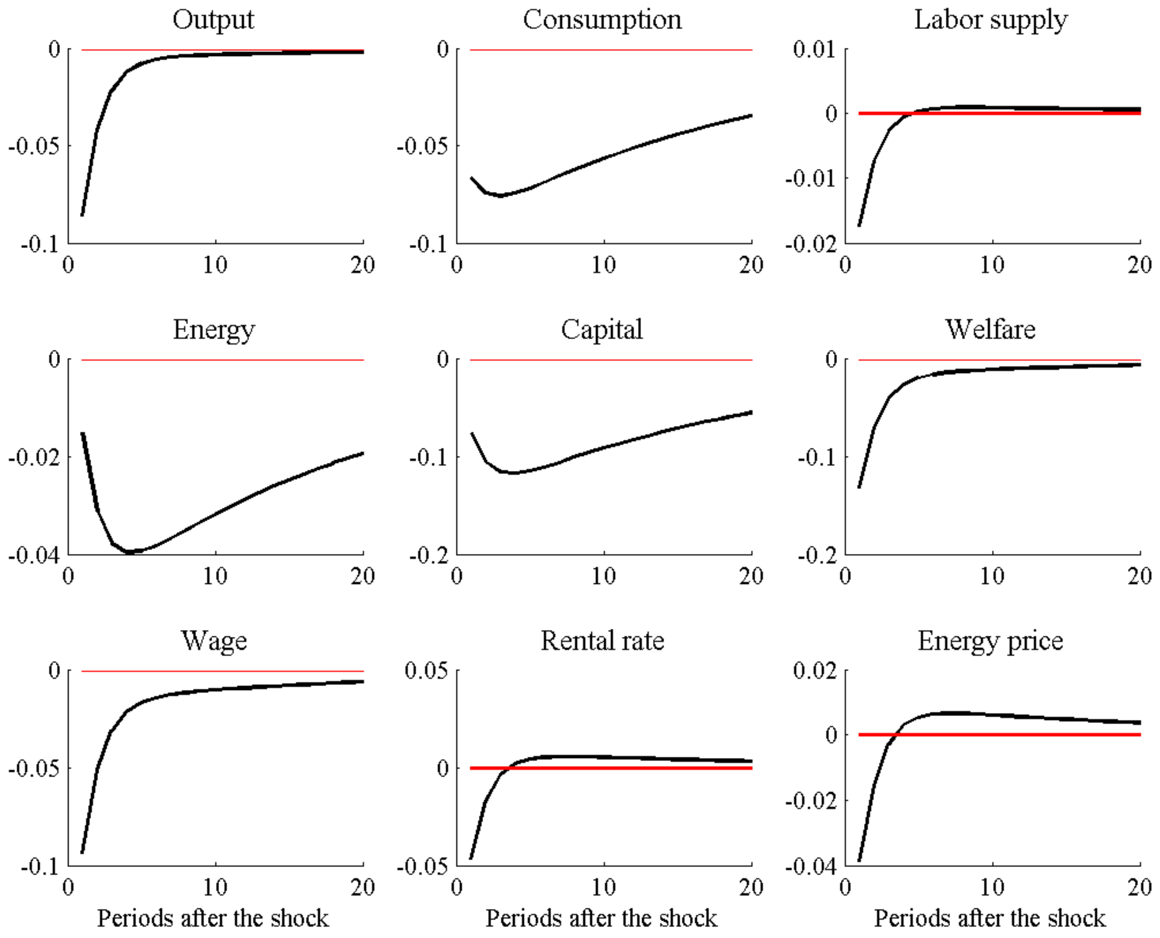

Figure 3: Impulse responses for a temporary increase in temperature (benchmark).

ranging from 0.0185°C (benchmark) to 2.0°C.

A permanent increase in global mean temperature reduces aggregate output with output (utility) damages ranging from 0.09 to 1.41 (0.02 to 0.42) percent of GDP (welfare). Notice that the output damage implied by our model is consistent with Nordhaus (2008) (see Figure 3-3, p. 51). When a permanent temperature shock hits the economy, for instance a 2.0°C temperature increase, dirty and green energy use falls substantially relative to the benchmark. This reduction in the use of energy (natural) resources increases welfare (agents dislike natural resources use, i.e., value nature), but not enough to compensate for the drop in GDP and, consequently, in consumption. Such permanent temperature increase of 2.0°C would imply a welfare loss of less than two percent of the benchmark welfare. When both temperature damage functions are considered, the consumption equivalent amounts to three percent of the annual GDP, meaning that an individual would require a three percent increase in her consumption to be as well off as in the benchmark case. The results of our analysis point to the notion that the effect of temperature in the economy is quite substantial. To put our results into perspective, consider the economy U.S. with a GDP of $18.57 trillion in 2016. Our model predicts that for a permanent 2.0°C temperature shift, the consumption equivalent welfare in the U.S. would be $557 billion or would be around $1,800 per person.

In summary, the presence of temperature anomalies in the utility function makes allocation choices

Table III: Responses of macroeconomic variables to climate change.

	Benchmark	Global mean temperature increase			
	0.0185°C	0.5°C	1.0°C	1.5°C	2.0°C
Welfare	-2.2071	-2.2095	-2.2164	-2.2279	-2.2442
Utility Damage (% of Welfare)	0.0000	0.0272	0.1083	0.2424	0.4278
Output Damage (% of GDP)	0.0000	0.0875	0.3505	0.7900	1.4078
Welfare loss (% of Benchmark)	0.0000	0.1045	0.4185	0.9424	1.6769
Consumption equivalent (% of GDP)	0.0000	0.1850	0.7422	1.6759	2.9936

and economic dynamics richer but more complicated. If households like to consume in a pleasant environment (i.e., in an economy that uses less natural resources in production), a rise in temperature lowers consumption and, as the representative household prefers minimal extraction of natural resources, temperature anomalies amplify the (negative) effect of natural resources use on the agent's utility. To the extent that negative shocks emanating from climate change as temperature anomalies affect natural resources, they could also be understood as a negative preference shock emanating from climate change (as temperature anomalies cause disutility).

4.3 Sensitivity Analysis: Additional Exercises

In this section we conduct additional exercises to study the predictions of our model by altering some of its benchmark features. First, we study the relevance of temperature damages to either agents' utility or production for the economy welfare in the short- and long-run. Second, we explore the impact of temperature anomalies in the long-run productivity instead of effects on the level of output. Third, we study how different values for the discount rate, the elasticity of substitution between different energy sources and parameters of the temperature stochastic process affect the economy's welfare. And, finally, we ask whether temperature shocks could potentially improve welfare.

4.3.1 Output, Utility Damages and Environmental Preferences

We now study the quantitative relevance of and the sensitivity of our results to output and utility damage functions for an economy facing temporary and permanent temperature shocks. The short run impact of climate change through the allocations of output, consumption, labor supply, and energy ultimately affect the welfare of households in the model. The short run response of welfare for unanticipated changes in temperature is depicted in Figure 4. The solid IRF ($-$) present the dynamic response of welfare for the benchmark case. As discussed in the previous section, an unanticipated two-degree Celsius increase in temperature lowers consumption, labor supply, and the energy composite, lowering welfare on impact. As the temperature shock tapers off, the model predicts that welfare will return to its steady state level after more than twenty years. The IRF with a circle ($- \circ -$) in the figure depicts the dynamic response of welfare for the case where $\theta_Y = 0$, i.e., no temperature damages to production. Although it behaves the same way as in the benchmark case, the reduction in welfare is much lower on impact for the case of $\theta_Y = 0$. The intuition here is that since temperature does not affect wages and other input prices directly, labor (leisure) does not decrease (increase) as much as in the benchmark case.

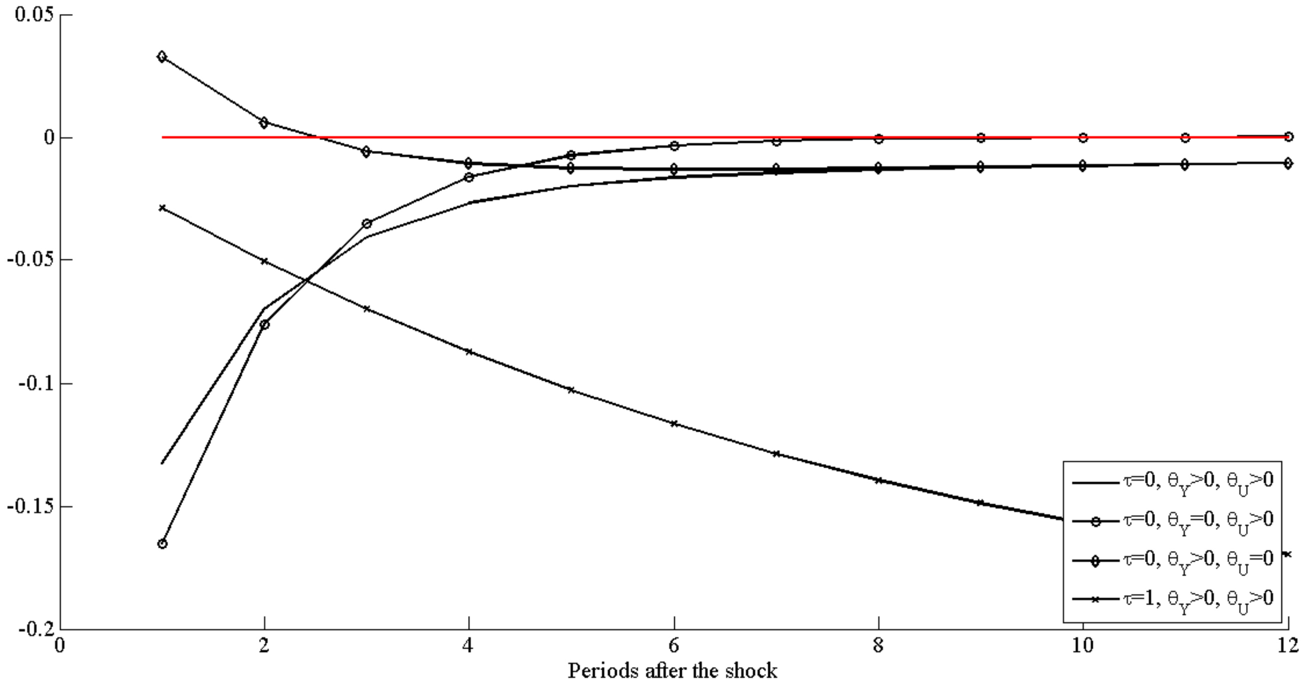

Figure 4: Impulse responses of welfare for a temporary increase in temperature with different values of θ_Y, θ_U and τ.

The dynamic response of welfare for the case of $\theta_U = 0$ (temperature does not damage utility directly) is presented in the IRF with a diamond ($-\diamond-$) in Figure 4. The response of welfare is remarkably different compared with the other cases. On impact, welfare rises initially and then decreases as it returns to its steady state along with the temperature anomaly. The initial increase in welfare can be explained by two effects: First, the absence of the direct impact of temperature in household preferences imply that welfare is only affected by its indirect effect, through damages to production, coming from consumption, leisure, and energy composite; And second, the temperature anomaly raises leisure and reduces the energy composite as a result of lower input prices. Regardless of the channel through which temperature affects the economy, we observe that the dynamic response of welfare is quite persistent. As shown in Figure 4, its takes welfare more than twenty years to revert back to its initial steady state value. This persistence demonstrates that even temporary changes in temperature has the potential to produce lasting effects in the economy, namely, it's production capacity and agents' well-being.

With respect to the effects of climate change (permanent temperature shifts), Table IV presents the results for the cases when temperature anomalies affect the economy either through damages to the output or damages to agents' utility. We also present the benchmark case (output and utility damages) for comparison. As expected, we first notice that temperature increases lead to welfare losses in all cases - output damage only, utility damage only and both, output and utility damages. Assuming that agents dislike energy use in production (in other words, the value nature), welfare losses measured either as percentage of benchmark welfare or consumption equivalent (% GDP) are bigger when temperature anomalies affect both output and utility ($\theta^Y(T), \theta^U(T) \neq 0$). Note, however, that depending on how

Table IV: Responses of macroeconomic variables to climate change.

	Benchmark	Global mean temperature increase			
	0.0185°C	0.5°C	1.0°C	1.5°C	2.0°C
Benchmark ($\theta_Y \neq 0$, $\theta_U \neq 0$, $\phi_E \neq 0$)					
Welfare	-2.2071	-2.2095	-2.2164	-2.2279	-2.2442
Welfare loss (% of Benchmark)	0.0000	0.1045	0.4185	0.9424	1.6769
Consumption equivalent (% of GDP)	0.0000	0.1850	0.7422	1.6759	2.9936
No output damage ($\theta_Y = 0$, $\theta_U \neq 0$, $\phi_E \neq 0$)					
Welfare	-2.2071	-2.2085	-2.2124	-2.2190	-2.2282
Welfare loss (% of Benchmark)	0.0000	0.0595	0.2383	0.5363	0.9535
Consumption equivalent (% of GDP)	0.0000	0.1052	0.4217	0.9494	1.6885
No utility damage ($\theta_Y \neq 0$, $\theta_U = 0$, $\phi_E \neq 0$)					
Welfare	-2.2071	-2.2081	-2.2111	-2.2161	-2.2230
Welfare loss (% of Benchmark)	0.0000	0.0449	0.1797	0.4038	0.7163
Consumption equivalent (% of GDP)	0.0000	0.0794	0.3186	0.7177	1.2777

temperature affects the economy imply different estimates for the welfare cost of temperature anomalies. For instance, at a 2.0°C temperature increase, the utility-damage case ($\theta^Y(T) = 0, \theta^U(T) \neq 0$) implies a welfare loss of about one percent of the benchmark welfare or a consumption equivalent of 1.7 percent of GDP, while the output-damage ($\theta^Y(T) \neq 0, \theta^U(T) = 0$) case implies losses of less than 1 and 1.3 percent, respectively. In the benchmark case, when both temperature damage functions are considered, the consumption equivalent amounts to three percent of the GDP. These differences can be potentially be associated with agents' behavior and adaptation to a permanent increase in temperature and whether temperature affects their utility directly and they value natural resources (environmental preferences).

The magnitude and the quantitative effects depend crucially on whether temperature increases having a direct impact on the utility of the individuals. Temperature damages to the agent's utility amplify the effects of temperature anomalies and climate change on the economy and welfare. While consumption and labor in the three cases fall by relatively similar amounts, agents reduce the use of energy inputs by a larger amount when their preferences are directly affected by temperature increases. On the other hand, physical capital fall relatively more when temperature anomalies affect allocations only through damages to output, i.e, when $D^U(T) = 1$ and $D^Y(T) \neq 1$. This distinct effect of temperature on factors of production E_1, E_2, and K can be explained by the intratemporal equilibrium conditions of the household (equations 11, 12 and 13). Notice that while the intratemporal condition between consumption and capital is affected by its price (r) and depreciation (adjusted by the investment cost), the intratemporal conditions have an additional term related to the disutility of energy inputs on production. With environmental preferences and an utility damage function, temperature anomalies increase the disutility of energy use leading agents to reduce their use more dramatically when temperature increases. We also observe the same behavior with respect to the investment in physical capital and energy inputs.

4.3.2 Temperature Anomalies and TFP

As discussed in the previous section, the adverse effects of temperature anomalies were introduced in the economy by means of a damage function on the level of GDP. Pindyck (2015) argues that damage functions have little theoretical basis and that the majority of economic research on climate change makes use of a loss function on the production function. Empirical evidence strongly support the negative correlation between extreme weather events and TFP (Dell et al., 2012; Donadelli et al., 2017). Thus, while useful in our analysis, modeling the level effects of temperature anomalies through damage functions may not be able to study other channels through which climate change could affect macroeconomic variables. In this section, we explore the impact of temperature anomalies in long-run productivity instead of effects on the level of output.

Following Donadelli et al. (2017), we re-specify the TFP process:

$$A_t = (1-\rho_A)\overline{A} + \rho_A A_{t-1} + \tau^T \xi^T_{t-1} + \xi^A_{t-1}, \tag{21}$$

The non-standard feature of equation (21) is the term $\tau^T \xi^T_{t-1}$ which represents the impact of temperature anomalies on TFP. Except for $\tau^T \xi^T_{t-1}$, we calibrate the rest of the parameters in the model in the same way as before (Table I). We set the value for τ^T to -1 so that productivity growth declines by about 0.1 percentage points after an unanticipated one-standard deviation increase in temperature and that it has a close enough correlation with GDP as in the data.

The impact of an unanticipated increase in temperature on welfare for the case where $\tau = -1$ is depicted in Figure 4. We can observe that welfare decrease on impact but its effect is very persistent compared to the other cases. The intuition for this persistence is that the temperature propagates through the TFP and that it assumes the persistence properties of the TFP process. The fact that temperature shocks also affects agent's utility directly ($\theta^U(T) \neq 0$) also contributes to this significant drop in welfare.

4.3.3 Discount Rate, Elasticity of Substitution and Temperature Stochastic Process Parameters

In this section we investigate the sensitivity of our benchmark results by considering a range of reasonable alternative values for key parameters. Although we could perform sensitivity analyses for all parameters, we restrict our attention to the discount rate, the elasticity of substitution between different energy sources and parameters of the temperature stochastic process as they affect the production and agent's utility functions.

The dynamic response of welfare with different key parameter values is depicted in Figure 5. The solid IRF ($-$) in the figure correspond to the dynamic response of welfare for the benchmark case. Given an unanticipated 2.0°C increase in temperature lowers welfare on impact primarily due to the decline in consumption. The following is a discussion of the effects of changing the the elasticity of substitution, discount factor, volatility of the temperature shock, and the persistence of the temperature shock. First, the IRFs with a circle ($-\circ-$) and diamond ($-\diamond-$) in the figure represent the dynamic response of welfare for when the elasticity of substitution is increased to $\rho = 0.39$ and $\rho = 0.50$, respectively. Although it

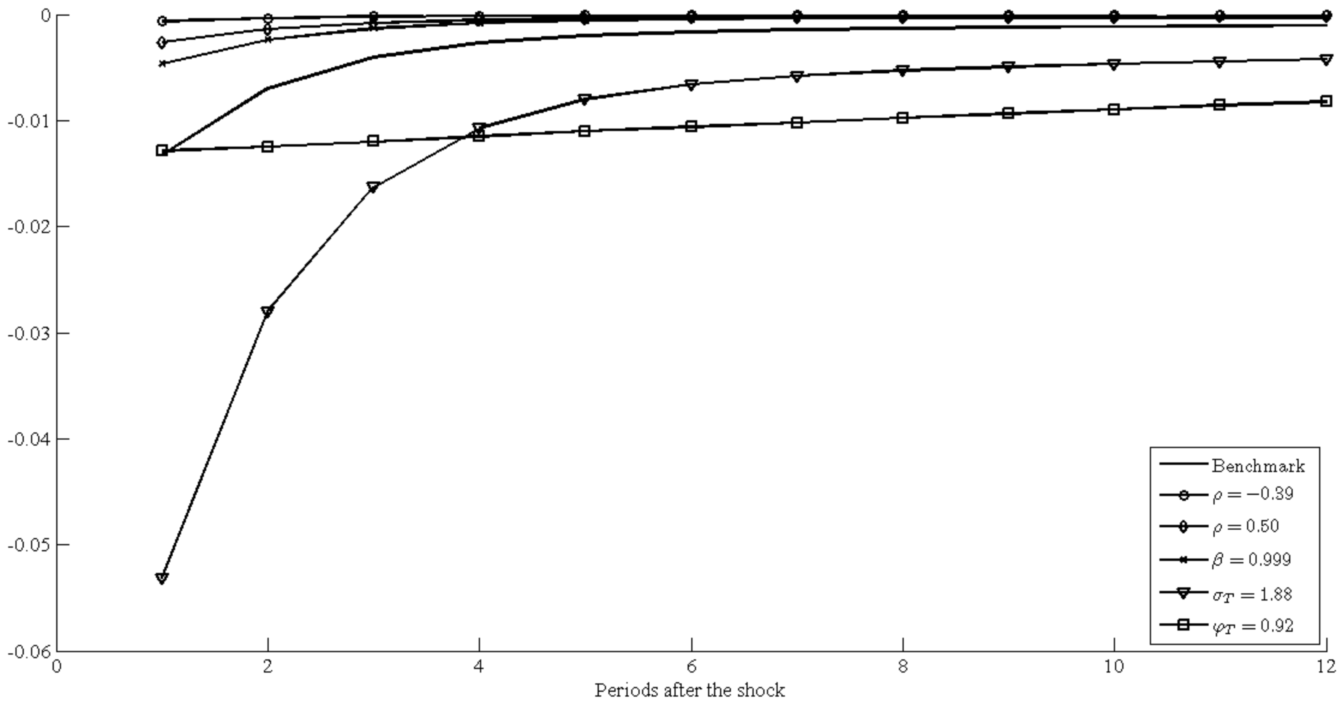

Figure 5: Impulse responses of welfare for a temporary increase in temperature with different values of ρ, σ_T and φ_T.

behaves the same way as in the benchmark case, the decrease in welfare is rather small on impact for the case of $\rho = 0.39$ and $\rho = 0.50$, respectively. The initial response of welfare is smaller in either case relative to the benchmark. Second, the IRF with an x mark $(- \times -)$ depict the case where the discount factor is increased from $\beta = 0.985$ to $\beta = 0.999$. As shown in the figure, increasing the discount factor makes the initial decrease in welfare less pronounced relative to the benchmark case. Similar to the case where we alter the elasticity of substitution value, we find that changing the discount factor did not change the qualitative feature of our main results. Third, doubling the volatility of the temperature shock (from $\sigma_T = 0.94$ to $\sigma_T = 1.88$ significantly deepen the initial decline in welfare as shown by the impulse response with triangle $(-\nabla-)$. Finally, the IRF with $(-\Box-)$ depict the dynamic response of welfare when the persistence of the temperature shock is increased to 0.92. The effect of increasing the persistence is that it takes a longer amount of time for the temperature shock to revert back to its steady state value. In all, we find that altering the aforementioned parameters does not change nor overturn our previous results.

4.3.4 Can Temperature Shocks Improve Welfare?

Consider an economy situated in a usually cold region (i.e. tundra or subarctic) where some resources are inaccessible and living conditions are not as good as those in temperate regions. One can hypothesize that temperature anomalies can bring about drastic changes in welfare and output in these regions. For instance, temperature increases can lead to the melting of ice in seaways that enable access to international trade. Another example would be that the melting ice makes previously inaccessible areas available for natural resource extraction. In this section we test the foregoing hypothesis by altering the properties of the damage functions. Precisely, we reverse the signs of θ_Y and θ_U to allow for improvements in output

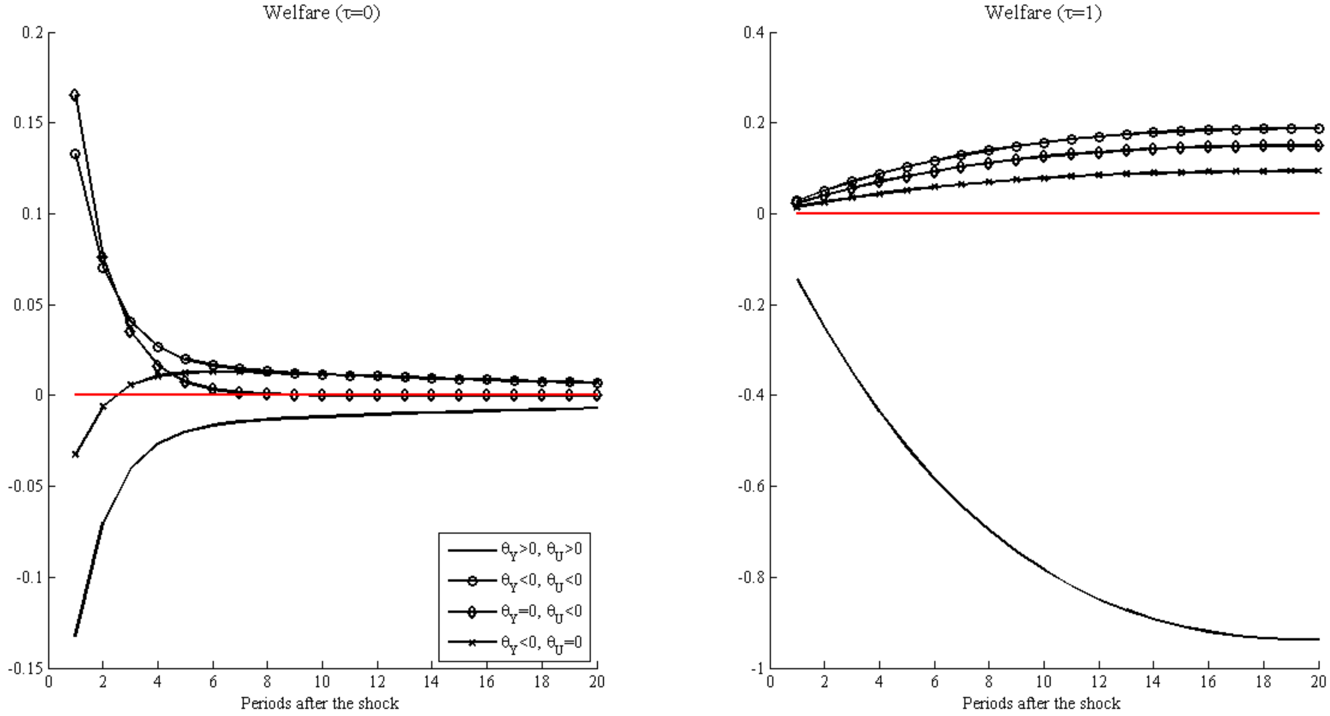

Figure 6: Impulse responses of welfare for a temporary increase in temperature, additional experiments.

and utility, respectively, as a result of an unanticipated increase in temperature.

The left panel of Figure 6 depicts the case where the temperature shock does not propagate through the TFP. As before, the solid IRF $(-)$ present the dynamic response of welfare for the benchmark case. On impact, welfare improves as temperature increases as shown by the IRF with circle $(-\circ-)$. This is the case where both θ_Y and θ_U are negative in sign. Welfare improves all the more for the case where θ_U is negative and we shut off the damage function in output as shown by the IRF with diamond $(-\diamond-)$. Finally, the IRF with $(-\times-)$ demonstrate the case where θ_Y is negative but θ_U is set to zero. In this final case we find a decrease in welfare on impact. The intuition for this result is that, since the utility channel is shut off, welfare deteriorates because of increases in labor supply and in the energy composite being good enough to offset the increase in consumption. The right panel of Figure 6 depicts the case where the temperature shock propagates through the TFP. We find that the behavior of temperature shock is akin to a positive TFP shock. Except for the benchmark case, we find that welfare improves and it takes a long time for it to revert back to the steady state value.

5 Conclusion

In this paper, we have explored and quantified the macroeconomic consequences of temporary (weather) and permanent (climate change) temperature shocks. We embedded the notion that temperature anomalies, defined here as deviations of temperature from its mean, affect household preferences and production technology and the fact that people value nature into an otherwise standard DSGE model. Our study departs from the current literature as we consider several channels through which temperature can influence the economy, as well as the role of energy use in household preferences. A permanent increase of temperature by 2.0°C lowers long-run GDP by as much as 1.4 percent and that the consumption equivalent welfare is around 3 percent of GDP. A temporary increase of a similar magnitude lowers aggregate variables and welfare on impact. Our results indicate that the impact of weather shocks and climate change to welfare is significant. Our analysis shows that direct temperature damages to the agent's preferences exacerbate the effects of temperature anomalies and climate change on the economy and welfare. The short-run response of welfare to an unanticipated change in temperature is remarkably different when temperature directly affects preferences than otherwise. On impact, welfare rises initially and then decreases as it returns to its steady state along with the temperature anomaly. The qualitative features of the predictions from our model are insensitive to altering the channels through which temperature affect the economy and for a reasonable range of parameter values.

Our analysis has abstracted from many important factors, particularly agents' heterogeneity and the role of fiscal policy. It is however a very flexible starting point and we foresee several ways through which our contribution can enrich future research in this field. First, our model can be extended to evaluate the role of fiscal policies in the face of weather shocks and climate change. For instance, future research can investigate the effectiveness of income redistribution and taxation policies to mitigate the adverse effects of climate change. Furthermore, our model can be extended to have several types of agents to study the heterogeneous effects climate change and income inequality. These avenues have a lot of policy implications which can be beneficial for the carving of future policies to mitigate the adverse effects of climate change.

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