WELFARE COSTS OF LONG-RUN TEMPERATURE SHIFTS

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ABSTRACT

This article makes a contribution towards understanding the impact of temperature fluctuations on the economy and financial markets. We present a long-run risks model with temperature related natural disasters. The model simultaneously matches observed temperature and consumption growth dynamics, and key features of financial markets data. We use this model to evaluate the role of temperature in determining asset prices, and to compute utility-based welfare costs as well as dollar costs of insuring against temperature fluctuations. We 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 2.46% of world GDP. If we allow for temperature-triggered natural disasters to impact growth, insuring against temperature variation raise to 5.47% of world GDP. We show that the same features, long-run risks and recursive-preferences, that account for the risk-free rate and the equity premium puzzles also imply that temperature-related economic costs are important. Our model implies that a rise in global temperature lowers equity valuations and raises risk premiums.

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1 Introduction

Given the prospect of global warming over the next century, the potential impact of temperature variation on GDP, aggregate consumption, and wealth is a matter of considerable importance. This article makes a contribution towards understanding the impact of temperature fluctuations on the macro-economy and financial markets. We present a long-run risks based equilibrium model that accounts for the observed temperature and consumption dynamics, and a wide-range of asset market returns and volatility puzzles. We use this model to ask, how large are the economic costs of temperature variation? That is, based on current economic state prices embedded in financial markets what are the dollar costs of insuring against temperature fluctuations, as well as utility-based welfare costs of temperature stabilization. Further, we use the model to evaluate the role of temperature in determining asset valuations.

The Stern Review (2007), and Stern (2008) argue that the overall costs associated with temperature risks are very large, they are equivalent to losing at least 5% of GDP each year, now and forever, and can be as high as 20% of GDP. However, these magnitudes have been questioned, both in terms of modelling assumptions and the inputs. Nordhaus (2007) argues that the Review's conclusions decisively depend on the assumption of a near zero discount rate and would not survive the substitution of discounting assumptions that are consistent with market facts. Indeed, an important focus of our approach is to consider a consumption-based asset pricing model, that is quantitatively consistent with a wide-range of financial market facts — this ensures that the stochastic discounting we utilize has a sound market basis. The analysis in the Stern Review (2007) and Nordhaus (2008) uses different calibrations of the power-utility model to evaluate climate change-related costs[1] Mehra and Prescott (1985) and Hansen and Jagannathan (1991), among others, show that the power-utility model cannot account for the equity premium and risk-free rate puzzles, and generally fails to account for a wide-range of financial market facts. This implies that the consumption-state prices embedded in this model for computing various costs are not consistent with market facts, and in this sense are implausible.

Our modelling approach to understand temperature related risks builds on the long-run

[1]Indeed, Stern uses a standard power-utility agent (log utility), with the time-discount of 0.999 and an assumed per-capita growth of 1.3% per annum, yielding a risk-free rate of 1.4%. Nordhaus, also uses a production-based model with power-utility model with risk-aversion at 2 and the pure-rate of time-preference of 1.5% — this yields a real-risk free rate of 5.5% per annum.

risks model of Bansal and Yaron (2004), who show that the model can jointly account for the observed consumption dynamics, the risk-free rate, the equity premium, and volatility puzzles among others. [2] The key ingredients in the model are the recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty, and a persistent expected growth component in consumption along with time-varying consumption volatility which allows for risk-premia fluctuations. We entertain an augmented LRR model in which temperature negatively impacts long-run growth, thus, temperature has a long-lasting effect on consumption growth. We also consider temperature-triggered natural disasters which cause a reduction in growth, i.e., negative growth jumps, to assess the impact of tail effects. Our long-run risks temperature model (LRR-T) model provides two potential channels through which temperature affects the aggregate economy and financial markets. A similar approach is followed in Pindyck (2011) where temperature is assumed to impact the growth rate of GDP as opposed to the level of GDP, and Nordhaus (2008) where temperature negatively affects TFP.

In terms of the model specifics, our long-run risks temperature model (LRR-T) assumes that temperature and growth follow a bivariate process, which is calibrated to match the data. In particular, the specification captures the negative impact of temperature on expected growth. In terms of the model implications, we show that a rise in temperature lowers the wealth-to-consumption ratio in the economy and that temperature shocks carry a positive risk premium in the economy when agents have a preference for early resolution of uncertainty. In contrast, with power utility and risk-aversion larger than one (as used in Nordhaus), temperature raises the aggregate wealth-to-consumption ratio, as the discount rate drops more sharply relative to expected growth. Further, the risk-premium for temperature risk is negative, as states in which temperature raises the aggregate wealth increases while consumption falls. This underscores the importance of the LRR-T model setup to evaluate temperature related issues. We also develop an augmented LRR model which includes temperature related natural disasters (i.e. negative jumps). We assume the likelihood of one disaster every hundred years, and a 1°C increase in temperature doubles the probability of a natural disaster in a year. The size of the negative temperature-related jumps is about -1.0% of consumption. Our calibration intends to explore the potential impact of

[2] Subsequent work has shown that the model can also explain observed credit spreads, term structure of interest rates, option prices, and cross-section of expected returns across assets. For the term structure of interest rates see Piazzesi and Schneider (2007), for credit spreads see Bhamra, Kuehn, and Strebulaev (2009), for cross-sectional differences in expected returns see Bansal, Dittmar, and Lundblad (2005) and Hansen, Heaton, and Li (2008), and for option prices see Drechsler and Yaron (2007)

tail events as in Pindyck (2011) and Weitzman (2009).

For our quantitative analysis we use the standard calibration for preferences laid out in Bansal and Yaron (2004). All of our model specifications match the joint consumption and temperature dynamics. Each of the models also matches the risk-free rate and the equity premium, as well as the volatility of returns, and the correlations between temperature and asset returns. Our target is also to match the premium on the consumption claim — Lustig, Van Neiuwerburgh and Verdelhan (2009) use flexible estimation methods to show that the premium on the consumption claim is 2.25%, and each of the models matches this feature as well.

For each of the variants of the model, we evaluate the welfare costs of temperature stabilization. As in Lucas (1987), we evaluate what is the amount of consumption that agents will be willing to pay to insulate consumption from temperature effects. Second, we evaluate the dollar costs of hedging temperature risk; we consider two consumption claims, one with and another without temperature exposure, and compute the difference in the price of these claims to ask how much should society be willing to pay to insure against temperature risks as current consumption state prices. Our dollar costs and the Lucas-style utility costs computations show that temperature fluctuations have a very significant economic impact. We find that the dollar costs are important, for the category 1 model the costs are 2.46% of World GDP and for the category 2 model the costs are 5.47% of World GDP. The costs are driven by the fact that the risk-premium on the zero-temperature exposed consumption claim is smaller than the one with temperature exposure. The long-run nature of temperature risks as well as the preference for early resolution for uncertainty are very important for these magnitudes. Similarly, the utility costs are significant, they are about 1%. These, as with the dollar costs, depend on the long-run nature of temperature risks.

The rest of the paper is organized as follows. In the next section we setup the long-run risks model, we present the solution to the model and discuss its theoretical implications for asset markets. In Section 3 we present our measures to assess the costs of temperature fluctuations. Section 4 describes the calibration of the economy and preference parameters, the model implications and results. Conclusion follows.

2 Long-Run Risks Temperature Model

Our long-run risks temperature model (LRR-T) model provides two potential channels through which temperature affects the aggregate economy and financial markets. First, temperature fluctuations negatively impact long-run growth. Second, an increase in temperature raises the likelihood of natural disasters. In this section we present the long-run risks temperature (LRR-T) model which introduces the impact of temperature on aggregate growth in the LRR model of Bansal and Yaron (2004), and discuss the connection between aggregate growth and temperature risks.

2.1 Preferences

As in the baseline LRR model, we represent the agent's preferences using Epstein and Zin (1989) and Weil (1990) type of recursive representation. An agent maximizes her lifetime utility,

$$V_t = \left[(1-\delta)C_t^{\frac{1-\gamma}{\theta}} + \delta\Big(E_t\big[V_{t+1}^{1-\gamma}\big]\Big)^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}, \tag{1}$$

where C_t is consumption at time t, $0 < \delta < 1$ reflects the agent's time preference, γ is the coefficient of risk aversion, $\theta = \frac{1-\gamma}{1-\frac{1}{\psi}}$, and ψ is the intertemporal elasticity of substitution (IES). Utility maximization is subject to the budget constraint,

$$W_{t+1} = (W_t - C_t)R_{c,t+1} \ , \tag{2}$$

where W_t is the wealth of the agent, and $R_{c,t}$ is the return on all invested wealth.

As shown in Epstein and Zin (1989), this preference structure implies the following (log) Intertemporal Marginal Rate of Substitution (IMRS),

$$m_{t+1} = \theta \ln \delta - \frac{\theta}{\psi}\Delta c_{t+1} + (\theta - 1)r_{c,t+1} \tag{3}$$

where $\Delta c_{t+1} = \ln(C_{t+1}/C_t)$ is consumption growth, and $r_{c,t+1} = \ln(R_{c,t})$ is the continuous return of an asset that pays a unit of consumption as dividend (i.e., return on wealth). This return is different to the return on the market portfolio since wealth not only includes stock market wealth but also human wealth, real estate, and other non-financial wealth. The sign of θ is determined by the magnitudes of the IES and the coefficient of risk aversion. When the risk aversion parameter equals the reciprocal of the IES, $\gamma = \frac{1}{\psi}$, then the model collapses to the case of power utility where the agent is indifferent about the timing of the resolution of uncertainty in the economy. As discussed in Bansal and Yaron (2004), when $\psi > 1$, $\gamma > 1$ and the risk aversion exceeds the reciprocal of the IES the agent prefers early resolution of uncertainty about the consumption path, which is the case adopted in the LRR model. Finally, for future reference, the notation for the multi-period stochastic discount factor to discount payoffs at date $t + j$ is denoted as

$$M_{t+1\rightarrow t+j} \equiv \exp\left(\sum_{k=1}^{k=j} m_{t+k}\right) \tag{4}$$

2.2 Consumption Growth Dynamics

As in Bansal and Yaron (2004), we assume that conditional expected consumption growth contains a small but persistent component x_t, and economic uncertainty is modelled as time-varying volatility σ_t allowing a time-varying risk. We assume temperature, w_t, affects aggregate consumption dynamics by adversely affecting long-run expected growth and by increasing the likelihood of natural disasters, D_{t+1}. Therefore, growth and temperature dynamics are described by,

$$\Delta c_{t+1} = \mu + x_t + \sigma_t \eta_{t+1} + \varphi_c D_{t+1} \tag{5}$$

$$x_{t+1} = \rho x_t + \sigma_t \varphi_e e_{t+1} + \tau_w \sigma_\zeta \zeta_{t+1} + \varphi_x D_{t+1} \tag{6}$$

$$w_{t+1} = \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \tag{7}$$

where μ is the unconditional mean of consumption growth, η_{t+1} is a standard Gaussian innovation that captures short-run risks. The expected growth rate shocks e_{t+1}, and temperature shocks ζ_{t+1} are also independent standard Normal innovations. The parameter $\tau_w \leq 0$ captures the impact of temperature shocks on long-run expected growth; therefore, if $\tau_w < 0$ implies a negative impact of temperature shocks on long-run expected growth. To capture the feature that growth raises temperature, we allow expected growth rate shocks to affect temperature with $\tau_x \geq 0$. The parameter ρ governs the persistence of x_t, and φ_e determines the magnitude of the standard deviation of the persistent component of consumption growth relative to the high-frequency innovation η_{t+1}. Mean and persistence in temperature are determined by μ_w and ρ_w, respectively.

In our model, disasters D_{t+1} follow a compensated compound Poisson process and are induced by temperature

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \xi_{i,t+1} - \lambda_t \mu_c, \tag{8}$$

where N_{t+1} is Poisson random variable with intensity λ_t and a jump size $\xi_{i,t+1}$. Therefore, the number of disasters at any point in time is N_{t+1}. We assume that the jump size is constant and equal to μ_c, and that the intensity of the Poisson process is increasing in temperature,

$$\lambda_t = \ell_0 + \ell_1(w_t - \mu_w) \tag{9}$$

where $\ell_0, \ell_1 > 0$, w_t denotes temperature, and μ_w its unconditional mean. This implies that the expected number of disasters, conditional on information at t, increases as temperature rises from its long-run mean, $E_t(N_{t+1}) = \lambda_t$. Our analysis entertains only negative jumps D_{t+1} in consumption growth, that is $\varphi_c = -1$. Disasters can potentially affect long-term expected growth, this is governed by φ_x. However, motivated by empirical considerations, in our calibrations we will set $\varphi_x = 0$ — that is, natural disasters will not affect long-run expected growth and therefore their impact on consumption growth will be completely transient and very short-lived. Nevertheless our model solutions can easily accommodate natural disasters with impacts on long-run expected growth. Our setup for negative jumps (natural disasters) is similar to that laid out in Eraker and Shaliastovich (2008) for LRR motivated models.

Finally, as shown in Bansal and Yaron (2004), to allow for time-varying risk premia we allow for varying consumption volatility. This volatility follows a simple process,

$$\sigma_t^2 = \sigma^2 + \nu(\sigma_t^2 - \sigma^2) + \sigma_v v_{t+1} \tag{10}$$

where v_{t+1} is an independent standard Normal innovation, ν determines the persistence of the variance of consumption growth, σ_v is the standard deviation of the variance process, and σ^2 is its unconditional mean. Time-varying volatility, as shown in Bansal and Yaron (2004) contributes to the risk premia but more importantly it allows for time-variation in the risk premia. In our setup, even if we abstract from time-varying volatility we still have a time-varying risk premia due to the time-varying nature of the conditional volatility of disasters, which depends on temperature. Nevertheless, we leave the varying consumption-volatility channel open to ensure that the quantitative implications of the model for risk premiums and price-volatility match the data closely.

2.3 Temperature, Wealth and Risk Prices

Using the standard asset pricing restriction for any continuous return, the continuous return on the wealth portfolio must satisfy,

$$E_t[\exp(m_{t+1} + r_{c,t+1})] = 1 \tag{11}$$

To solve for the return on wealth (the return on the consumption asset), we use the log-linear approximation for the continuous return on the wealth portfolio, namely,

$$r_{c,t+1} = \kappa_0 + \kappa_1 z_{c,t+1} + \Delta c_{t+1} - z_{c,t}, \tag{12}$$

where $z_{c,t} = \log(P_t/C_t)$ is log price to consumption ratio (i.e., the valuation ratio corresponding to a claim that pays consumption) and κ's are log linearization constants.[3] In the Appendix we show that the solution for the price-consumption ratio is affine in the state variables

$$z_{c,t} = A_0 + A_x x_t + A_\sigma \sigma_t^2 + A_w w_t \tag{13}$$

[3] These constants are equal,

$$\begin{aligned} \kappa_0 &= \ln\left(1 + e^{z_c}\right) - \frac{e^{z_c}}{1 + e^{z_c}} z_c, \\ \kappa_1 &= \frac{e^{z_c}}{1 + e^{z_c}}, \end{aligned}$$

where $z_c = E(z_{c,t})$.

where A_x, A_w, and A_σ must satisfy,

$$
\begin{aligned}
A_x &= \frac{\left(1-\frac{1}{\psi}\right)+\kappa_1 A_w \tau_x}{1-\kappa_1\rho} && (14)\\
A_\sigma &= \frac{\frac{1}{2}\theta\left[\left(1-\frac{1}{\psi}\right)^2+(\kappa_1 A_x \varphi_e)^2\right]}{1-\kappa_1\nu} && (15)\\
A_w &= \frac{\ell_1\left[\Phi[(1-\gamma)\varphi_c+\theta\kappa_1 A_x\varphi_x]-1\right]}{\theta(1-\kappa_1\rho_w)} && (16)
\end{aligned}
$$

where $\Phi(\tau)=\exp(\tau\mu_c)-\tau\mu_c$, and the expression for A_0 is presented in the Appendix along with further details about the solution.

The impacts of expected growth and consumption volatility on the price to consumption ratio are determined by the preference configuration. Higher expected growth raises asset valuations and the price to consumption ratio only when the IES is larger than one. Similarly, a rise in consumption volatility lowers the price to consumption ratio when the IES is larger than one. Temperature impact on asset valuations is determined by A_w, which is different to zero only if natural disasters have an impact on the economy (i.e. $\varphi_c \neq 0$ and/or $\varphi_x \neq 0$). Figure I plots A_w for various values of the IES. If the IES is less than one then temperature will raise asset valuations, while IES larger than one is needed for temperature to lower the aggregate wealth to consumption ratio.

Replacing the solution for the return on wealth on the expression for the IMRS (3), the innovation to the pricing kernel conditional on the time t information at time $t+1$ equals,

$$
m_{t+1}-E_t(m_{t+1}) = -\lambda_\eta\sigma_t\eta_{t+1}-\lambda_e\sigma_t e_{t+1}-\lambda_v\sigma_v v_{t+1}-\lambda_\zeta\sigma_\zeta\zeta_{t+1}-\lambda_D D_{t+1} \qquad (17)
$$

where λ_η, λ_e, λ_v, λ_ζ, and λ_D are the market prices of risks, which are equal to:

$$
\begin{aligned}
\lambda_\eta &= \gamma\\
\lambda_e &= (1-\theta)\kappa_1 A_x\varphi_e\\
\lambda_v &= (1-\theta)\kappa_1 A_\sigma\\
\lambda_\zeta &= (1-\theta)\kappa_1(A_x\tau_w+A_w)\\
\lambda_D &= (1-\theta)\kappa_1 A_x\varphi_x+\gamma\varphi_c
\end{aligned}
$$

As in the standard LRR framework, λ_η, λ_e, and λ_v are the market prices for the short-run, long-run, and volatility risks. In our framework, innovations on temperature and natural disasters are also priced, λ_ζ and λ_D. If the risk aversion coefficient equals the inverse of the IES, as in the case of CRRA preferences, then $\theta = 1$ and long-run risks, volatility risks, and temperature risks carry a zero risk compensation. That is, only short-run risks are priced in equilibrium. Note that when natural disasters do not affect long-run growth, i.e., $\varphi_x = 0$, they are compensated exactly in the same manner as short-run risks.

Combining the expressions for the he return on aggregate wealth and the IMRS, the risk premium, is determined by $-\text{cov}_t(m_{t+1}, r_{m,t+1})$, and equals,

$$E_t(r_{c,t+1} - r_{f,t} + \frac{1}{2}V_t(r_{c,t+1})) \;=\; \beta_\eta \lambda_\eta \sigma_t^2 + \beta_x \lambda_e \sigma_t^2 + \beta_v \lambda_v \sigma_v^2 + \beta_\zeta \lambda_\zeta \sigma_\zeta^2 + \beta_D \lambda_D \lambda_t u_c^2 \quad (18)$$

where $r_{f,t}$ is the risk-free rate, β_η, β_x and β_v are the betas of the asset return with respect to the short-run risk, long-run risk, and volatility risk innovations, respectively. The exposure to temperature is determined by the beta of temperature innovations, β_ζ, and the beta of natural disasters β_D. As the market prices of risk, all asset betas are endogenous to the model and depend on preference and model dynamics parameters. The risk compensation from each source of risk is determined by the asset's β for that risk times the market price of that risk, λ.[4]

The risk compensation for temperature shocks, $\beta_\zeta \lambda_\zeta$, is positive only when agents have a preference for early resolution of uncertainty and the IES is larger than one. Figure II depicts the risk compensation from temperature innovations for different values of the IES and a risk aversion parameter equal to 10. As noted above, the market price of risk is zero when agents have CRRA preferences, i.e., $\psi = \frac{1}{\gamma}$. Moreover, the temperature beta is zero since long-run risks have no impact on asset valuations, A_x equals zero. For values of the IES between the CRRA case, $\psi = \frac{1}{\gamma}$, and 1, temperature shocks contribute negatively to the risk premia. In this case, the market price of temperature risk λ_ζ is negative, but the beta of temperature innovations $\beta_{c,\zeta}$ is positive since long-run growth decreases the value of assets, i.e., A_x is negative. For values of the IES larger than one, the beta of temperature innovations is negative because temperature innovations negatively impacts long-run growth, thereby, asset prices.

The risk-free rate can be derived using the solution to the IMRS. In the Appendix we

[4]The expressions for the beta's are presented in the Appendix.

show that the risk-free rate is affine in the state variables. In particular, the loading on the expected growth rate x_t is positive and equal to the inverse of the IES, while the loading in volatility as well as temperature is negative under our baseline assumptions. Therefore, in our model an increase in temperature will lower the risk-free rate. Following Bansal and Yaron (2004), we also derive the implications of the model about the equity premium. A detailed derivation can be found in the Appendix.

3 Economic Costs of Temperature Variation

3.1 Dollar Costs of Temperature Variation

To asses the economic costs of temperature we compute the difference in the market price of an asset that pays consumption as dividend and an asset that pays consumption after insuring it from all effects of temperature. The insured consumption claim C_t^*, $t = 1 \cdots \infty$, corresponds to the case where $\tau_w = 0$, $\varphi_c = 0$, and $\varphi_x = 0$; the resulting consumption process is insured in all states and dates against temperature fluctuations. Thus, the difference in the price of C^* and C is the premium, in dollar terms, that the society might be willing to pay to insure against the effects of temperature at current consumption state prices. The equilibrium prices are determined by the consumption dynamics C_t, $t = 1 \cdots \infty$, which include the temperature dynamics as described in equation (5).

More precisely, the market price of a consumption claim is given by,

$$P_t = \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j} C_{t+j}] \tag{19}$$

where M is the stochastic discount factor based on our model. Similarly, the price of an asset that pays consumption exempt from the effects of temperature in the economy is given by,

$$P_t^* = \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j} C_{t+j}^*] \tag{20}$$

Given the value of consumption at date zero (start date), we can recover the prices of these two assets using the difference in the wealth-consumption ratio times the consumption at date zero. Therefore, we compute the dollar costs of temperature fluctuations as,

$$\text{Dollar Costs } = \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j}C^*_{t+j}] - \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j}C_{t+j}] \tag{21}$$

To compute the dollar costs we calculate the price-consumption ratio in both cases, with and without temperature risks, inside the model, and multiply its difference by the level of world consumption for the year 2009, i.e., we assume that initial aggregate consumption equals that of 2009.[5]

3.2 Welfare Costs of Temperature Variation

In the spirit of Lucas (1987), we explore the welfare gains of eliminating the effects of temperature variation on consumption. Let $C = \{C_t\}_{t=0}^{\infty}$ be the stream of consumption in an economy with temperature effects, and $C^* = \{C_t^*\}_{t=0}^{\infty}$ be the consumption stream in an economy without temperature effects (i.e, we set $\tau_w = 0$, $\varphi_c = 0$, and $\varphi_x = 0$). We define the welfare costs of temperature variation as the percentage increase in consumption $\Delta > 0$ that one must give to the agent (in every date and state) to make the agent indifferent between the stream of consumption which contains temperature risks, and the stream of consumption without temperature effects. Therefore, this compensating variation Δ must satisfy,

$$E\Big[U_0\Big(C\Big)\Big] = E\Big[U_0((1+\Delta)C^*)\Big] \tag{22}$$

Our derivation of the costs of economic uncertainty is based on exploiting the close connection between lifetime utility and the wealth-consumption ratio. Under Epstein-Zin preferences the lifetime utility of the agent normalized by current consumption is entirely determined by the wealth-consumption ratio, and the intertemporal elasticity of substitution. Note that under Epstein-Zin preferences we have a convenient expression that links current utility U_t and the consumption-wealth ratio,

$$\frac{U_t}{C_t} = (1-\delta)^{\frac{\psi}{\psi-1}} \frac{C_t}{W_t}^{\frac{\psi}{1-\psi}} \tag{23}$$

[5]The solution for the price-consumption ratio without temperature effects is presented in the Appendix.

Let $Z_{c,t} = \frac{P_t}{C_t}$ be the price-consumption ratio, and note that wealth equals $W_t = C_t + P_t$ which implies that $1 + Z_{c,t} = \frac{W_t}{C_t}$, then, the normalized lifetime utility equals to,

$$\frac{U_t}{C_t} = (1-\delta)^{\frac{\psi}{\psi-1}}(1+Z_{c,t})^{\frac{\psi}{\psi-1}} \tag{24}$$

Using this connection between asset prices and the life-time utility, the compensating consumption change for eliminating the negative effects of temperature variation on consumption, i.e., Δ, satisfies,

$$1+\Delta = \frac{E\left[(1+Z_c^*)^{\frac{\psi}{\psi-1}}\right]}{E\left[(1+Z_c)^{\frac{\psi}{\psi-1}}\right]}. \tag{25}$$

The magnitude of welfare costs of temperature variation are determined by comparing the wealth-consumption ratio in an economy with and without temperature risks on consumption, Z_c and Z_c^* respectively.

4 Model Implications

4.1 Data Sources

We calibrate the model to capture world temperature dynamics, world growth, and world risk premium. The data on global temperature covering the period 1929–2009 are obtained from the Intergovernmental Panel on Climate Change Data Distribution Centre and comes from the Climate Research Unit (IPCC fourth assessment (2007)). Land temperature is constructed using surface air temperature from over 3,000 monthly station records which have been corrected for non-climatic influences (e.g., changes in instrumentation, changes in the environment around the station, particularly urban growth). [6] Annual temperature data corresponds to the average of monthly observations. Stock market data come from Morgan Stanley Capital International (MSCI) equity index. We consider the MSCI All Country

[6]To compute large-scale spatial means, each station is associated to a grid point of a $5° \times 5°$ latitude-longitude grid, and monthly temperature anomalies are computed by averaging station anomaly values for all months. Finally, global temperature data are computed as the area-weighted average of the corresponding grid boxes and the marine data, in coastlines and islands, for each month.

World Index which measures equity returns across developed and emerging markets, 45 countries in total, to compute the world market equity return. We use the three-month T-bill rate to compute the risk-free rate. Real returns for all countries are obtained adjusting for U.S. inflation computed using the personal consumption expenditures (PCE) deflator from the National Income and Product Accounts (NIPA) tables. Data on world real GDP and real consumption come from the World Bank Development Indicators and cover the period 1960-2007.

Table I presents summary statistics for temperature dynamics, annual world GDP, consumption per capita growth, the world market real equity return, and the risk-free rate. The average global temperature is 14°, its volatility reaches 0.21 and its autoregressive coefficient equals 0.87. The average real GDP growth equals 1.91% while the average world consumption growth is about 1.84%. GDP growth volatility is around 1.4% and its autoregressive coefficient equals 0.44 while consumption growth volatility is nearly 1% and its autoregressive coefficient equals 0.41. The world market return is 6.83%, and the market return volatility equals 19.65%. The real risk-free rate averages 1.45% per annum, and its volatility is 2.03%, one-tenth of that of equity.

4.2 Calibration

As is standard in the literature, we assume that the decision interval of the agent is monthly. Table II presents the parameter configuration we use to calibrate the model, which we choose in order to match the joint dynamics of consumption growth and global temperature, the level of the risk-free rate, and the risk premium. Our baseline parametrization for preferences and the dynamics of consumption is very similar to that used in the long-run risks literature (e.g., Bansal, Kiku, and Yaron (2007a)). The subjective discount factor δ equals 0.999, the risk aversion parameter γ and the intertemporal elasticity of substitution ψ are equal to 10 and 1.5, respectively. Under this configuration, the agent has a preference for early resolution of uncertainty as in the long-run risk literature (e.g., Bansal and Yaron (2004)). As in Bansal, Kiku, and Yaron (2007a), we capture the persistence, volatility, and autocorrelations of consumption growth by calibrating the persistence of expected growth ρ, as well as φ_e and σ.

In the paper we entertain alternative models classified by the impact that temperature has on the economy. Category 1 model: only temperature innovations have an impact on the long-run component of growth, therefore we abstract from the effects of natural disasters, i.e., $\varphi_c = 0$ and $\varphi_x = 0$; Category 2 model: not only innovations in temperature impact expected growth, but also disasters have an impact on the high-frequency component of growth, $\varphi_c = -1$ and $\varphi_x = 0$.

To calibrate the the impact of temperature innovations on expected growth τ_w we aim to match the response world consumption growth to a temperature shock. Figure III depicts the impulse-response function obtained from a bi-variate VAR model of consumption growth and global temperature. In particular, it shows that a one standard deviation shock to temperature, about 0.2°C, reduces growth by 0.3% and its impact persists for up to twenty years. We choose a value of τ_w equal to -0.0018 which implies a negative response of consumption growth to temperature as observed in the data. In the model, a temperature shock reduces temperature up to 0.2%, and has a non-negligible impact for up to twenty years, as in the data. More importantly, the response of consumption lies within the 95% confidence intervals of the empirical VAR model (see Figure IV). This calibration is also consistent with the empirical evidence in Bansal and Ochoa (2011) where we show that global temperature and shocks to global temperature have a negative impact on economic growth. Using a panel of 147 countries we show that a one standard deviation shock to temperature, about 0.2°C, lowers GDP growth by 0.24%. Moreover, our results indicate that temperature not only has a contemporaneous short-lived impact on economic growth, but its negative impacts tend to persist over time. Dell, Jones and Olken (2009b) also show that an increase in temperature reduces GDP growth. Namely, a 1°C degree increase in temperature reduces growth by 1.1 percentage points for countries poor countries.

We set the compensated compound Poisson shock such that the probability of a natural disaster in a year is 1%, in other words, we assume the likelihood of one disaster every hundred years. We calibrate the sensitivity of the Poisson shock to temperature such that a 1°C increase in temperature doubles the probability of a natural disaster in a year. Therefore mean intensity of natural disasters ℓ_0 is set equal to 0.01/12 and its sensitivity to temperature ℓ_1 is equal to 0.01/12. We set the size of the Poisson jump μ_c such that the cost of a natural disasters equals 1.0% permanent reduction in consumption. As in Pindyck (2011) and Weitzman (2009), our calibration intends to explore the potential impact of tail events.

To make the model-implied data comparable to the observed annual data, we appropriately aggregate the simulated monthly observations and construct annual growth rates and annual asset returns. The model implications are obtained from population values that correspond to the statistics constructed from $12 \times 20,000$ monthly simulated data aggregated to annual horizon.

4.3 Asset Pricing Implications

Our calibration of the model captures the bivariate dynamics of consumption and temperature. Table III presents the model implications for the consumption growth and temperature dynamics. In all of our specifications the first-order autocorrelation of consumption is around 0.43, which is very close to the data. Similarly, the model calibration matches the autocorrelation of temperature. As seen in Figures III and IV the model also captures the negative and long-lasting response of consumption growth to temperature. The negative correlation between growth rates and temperature arises from the fact that temperature shocks impact negatively the expected growth rate of consumption, x_t. Even in the presence of natural disasters, shutting down this channel prevents the model from accounting for this feature of the data.

In our framework, where agents are not indifferent about the timing of uncertainty resolution, temperature risks are priced and contribute to the risk premium on the consumption claim as well as to the equity risk premium. Using the expression for the consumption risk premium, equation (18), we find that in the category 1 model the risk compensation for temperature accounts for about 1.1 basis points of the total risk premium on the consumption claim of 2.04%. Including the possibility of natural disasters, in the category 2 model, the temperature impact on long-run growth accounts for 1.1 basis points of the risk premium while natural disasters account for only 0.1 basis points, therefore temperature accounts for 1.2 basis points of the risk premium. Therefore, the risk premium on the consumption claim in category 2 model is slightly larger than category 1, but the difference is very small. The figures on the risk premium for the consumption asset are very close to the results of Lustig, Van Neiuwerburgh and Verdelhan (2009), who find that the consumption risk premium is 2.2% per year, and the discount rate on the consumption claim is 3.49% per year.

The model also matches the moments of the risk-free rate, and the market return (see Table III). The risk-free rate, in category 1 and category 2 models is about 1.1%, and the volatility of the risk-free is about 1.14%; for both models the levels and volatility match the data well. On the other hand, the return on the equity claim is higher and more volatile.

For category 2 the expected market return is 7.07%, with a volatility equal to 18.90%, giving rise to an equity premium of about 6%; the premium is slightly higher in the category 2 model. Moreover, the magnitude and volatility of equity returns are six times higher than the magnitude and volatility of the return on consumption. As in the LRR model of Bansal and Yaron (2004) the risks associated with the long-run growth are critical for explaining the risk premium in the economy, as it not only accounts for a significant portion of the premium but also magnifies the contribution of the volatility risk.

4.4 Dollar Costs of Temperature Variation

The second panel of Table IV presents the price-consumption ratio and the return on a asset that delivers the consumption stream, C^*, as its dividends. In all cases, as expected, the asset which removes the effects of temperature variation has a higher price-consumption ratio as it is insured against temperature related risks. The first panel of the table presents the difference in the price of an asset paying consumption with and without the effects of temperature in US$ dollars of 2009, which represent the losses in US$ dollars from temperature variation as priced by financial markets.[7] The dollar losses from temperature in our models range from 1.43 US$ trillion to 3.18 US$ trillion dollars, which imply a loss from 2.46% to 5.47% of GDP.

The key driver of these dollar costs is the change in the riskiness of the consumption claim. For example, in the category 2 model, the expected return on the consumption claim with temperature risk included is 3.29%, while the expected return of the consumption claim without temperature risks is 3.23%; the difference is about 0.06%. This leads to a price-consumption ratio that is higher in the case without temperature risk relative to the one with it. For example, in the category 2 model the difference in the annualized price-consumption ratio is $75.05 - 74.98 = 0.07$. This magnitude multiplied by 2008 World aggregate consumption translates to about 3.18 US$ trillion dollars.

[7]We use World consumption for the year 2009 to compute the price of these assets as explained in section 3.

4.5 Welfare Costs of Temperature Variation

In the spirit of Lucas (1987) costs of business cycles, we start by asking how much individuals would be willing to give up, in terms of percentage annual consumption, to live in a world exempt from the effects of temperature. The first row of Table V presents the welfare costs of temperature variation for the two alternative models we entertain. In the category 1 model, when only innovations to temperature have an impact on expected growth, welfare costs are equal to 0.78Natural disasters have only a small impact relative to temperature shocks because the size of the disasters are quite small and more importantly, they are transient and do not affect long-run growth. When φ_x is positive, natural disasters lower long-run growth and in this case their impact on welfare can be quite significant. However, for the most part, evidence indicates that natural disasters have only a short run impact on growth (see e.g Rasmussen (2004)), and for this reason we set $\varphi_x = 0$

To interpret these magnitudes for our two models it is useful to recall that welfare costs computations of eliminating business cycles reported in Lucas (1987) and much of the literature (see Barlevy (2004) for a review) are quite small, well less than 1% of GDP; hence our magnitudes of welfare-costs for temperature stabilization are in the upper bound to those typically reported for business cycles. Furthermore, in line with our findings, Pindyck (2011) shows that, in a model in which agents have uncertainty about temperature dynamics and its impact on growth, welfare costs are below 2% for parameter values consistent with scientific studies assembled by the International Panel on Climate Change (IPCC).

4.6 Interpreting Temperature Related Costs

Two key ingredients in the Bansal and Yaron (2004) LRR model explain the sizeable dollar and welfare costs associated with temperature fluctuations; (i) the recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty, and (ii) a standard long-frequency fluctuation for consumption growth with a persistent expected growth component. Table VI presents the simulations of our specifications first assuming that preferences are described by a CRRA utility function, i.e. $\gamma = \frac{1}{\psi}$ but otherwise maintain the LRR specification (CRRA-LRR) for growth rates. We also simulate the model keeping the original assumption of recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty but letting consumption be *iid*, thus temperature innovations and natural disasters impact its high frequency component (EZW-hf). In all exercises we keep the relevant parameter values same as our calibration, and in the EZW-hf we calibrate the standard deviation of the high frequency innovation such that it equals the monthly consumption volatility for our category 1 model.

In the CRRA-LRR model, two important results stand out. First, welfare costs of temperature variation are less than one-fifth of those that arise in our model. Second, temperature increases lead to an increase in the value of the consumption asset, which implies that more risk in the economy due to temperature makes the consumption claim more valuable; this is entirely due to the fact that the IES is less than one and that reductions in expected growth lowers the risk-free rate and the discount factor in the economy. Moreover, the model generates a risk-free rate of about 16% with a volatility of the same magnitude, and the equity premium is about 1.3%, all of which are far from their data counterparts; hence, this model specification cannot pass the market-test. In the last two columns we present the results for our two specifications for the EZW-hf case. Under this scenario, even though temperature leads to a reduction in asset prices, the welfare costs of temperature innovations are less than 0.1%, that is, ten times lower than our estimates. More importantly, the model implies a too small equity risk-premium, and a risk-free rate that is somewhat higher than the data. The model also significantly undershoots on the volatility of the price-dividend ratio (not reported in table) and the volatility of the risk-free rate. The welfare costs in this case are quite small compared to our category 1 or category 2 models. This lower cost magnitudes reflect the fact that the model does not have the long-run risks needed to match financial markets risks. In all, this evidence implies that the same features, long-run risks and recursive-preferences, that capture the risk-free rate and the equity premium puzzles also imply that temperature-related economic costs are significant.

5 Conclusions

This paper makes a contribution towards understanding the impact of temperature fluctuations on the economy and financial markets. We present a temperature related long-run risks equilibrium model, which simultaneously matches the observed temperature and growth dynamics, and key dimensions of the financial markets data. We use this model to evaluate the role of temperature in determining asset prices, and to compute the utility-based welfare costs as well as the dollar costs of insuring against temperature fluctuations. Our model implies that if temperature were to rise it would lower long-run growth, raise risk-premiums, and adversely affect asset prices — the magnitude of these negative effects increases with temperature, suggesting that global warming presents a significant risk. We 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. We show that the same features, long-run risks and recursive-preferences, that account for the risk-free rate and the equity premium puzzles (among others) also imply that temperature-related costs are important and that temperature-risks carry a positive risk premium. In future work an important ingredient, as appropriately emphasized by Weitzman (2009), is to incorporate temperature-related model uncertainty in the analysis.

Appendix

A Model solution

We assume that the state of the economy is described by the following system,

$$
\begin{aligned}
\Delta c_{t+1} &= \mu_c + x_t + \sigma_t \eta_{t+1} + \varphi_c D_{t+1} && (26)\\
x_{t+1} &= \rho x_t + \sigma_t \varphi_e e_{t+1} + \tau_w \sigma_\zeta \zeta_{t+1} + \varphi_x D_{t+1} && (27)\\
w_{t+1} &= \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} && (28)\\
\sigma_{t+1}^2 &= \sigma^2 + \nu(\sigma_t^2 - \sigma^2) + \sigma_v v_{t+1} && (29)
\end{aligned}
$$

where η_{t+1}, ζ_{t+1}, e_{t+1} and v_{t+1} are independent standard Normal innovations, and D_{t+1} is a compensated Poisson process,

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \xi_{i,t+1} - \lambda_t \mu_c \tag{30}$$

where N_{t+1} is a Poisson random variable with intensity λ_t and jump size $\xi_{i,t+1}$ is constant and equal to $\mu_c \in \mathbb{R}_+$. We assume $\lambda_t = \ell_0 + \ell_1 (w_t - \mu_w)$.

A.1 Solution for the Consumption Claim

To obtain the pricing kernel we first solve for the return on the consumption claim, $r_{c,t+1}$. The price of a consumption claim asset must satisfy,

$$E_t(\exp(m_{t+1} + r_{c,t+1})) = 1$$

Combining the expressions for the pricing kernel (3) and the log-linear approximation of the return on the consumption claim asset (12) we have,

$$E_t[\exp(m_{t+1} + r_{c,t+1})] = E_t\left[\exp\left(\theta \ln \delta + \theta\left(1 - \frac{1}{\psi}\right)\Delta c_{t+1} + \theta\kappa_0 + \theta\kappa_1 z_{c,t+1} - \theta z_{c,t}\right)\right] \tag{31}$$

Assuming that the solution for the price-consumption ratio is affine in the state variables

$z_{c,t} = A_0 + A_x x_t + A_\sigma \sigma_t^2 + A_w w_t$, and replacing Δc_{t+1} we have that,

$$\begin{aligned}
m_{t+1} + r_{c,t+1} &= \theta \ln \delta + \theta \left(1 - \frac{1}{\psi}\right) \mu + \theta \kappa_0 + \theta A_0 (1-\kappa_1) + \theta \kappa_1 \sigma^2 (1-\nu) A_\sigma + \theta \kappa_1 A_w (1-\rho_w) \mu_w \\
&+ \theta \left[\left(1 - \frac{1}{\psi}\right) + \kappa_1 A_w \tau_x - A_x (1 - \kappa_1 \rho)\right] x_t + \theta A_\sigma (\kappa_1 \nu - 1) \sigma_t^2 + \theta A_w (\kappa_1 \rho_w - 1) w_t \\
&+ \theta \left(1 - \frac{1}{\psi}\right) \sigma_t \eta_{t+1} + \theta \kappa_1 A_\sigma \sigma_v v_{t+1} + \theta \kappa_1 A_x \varphi_w \sigma_t e_{t+1} \\
&+ \theta \kappa_1 \left(A_x \tau_w + A_w\right) \sigma_\zeta \zeta_{t+1} + \left[\theta \left(1 - \frac{1}{\psi}\right) \varphi_c + \theta \kappa_1 A_x \varphi_x\right] D_{t+1}
\end{aligned}$$

In order to compute the expectation $E_t[\exp(m_{t+1} + r_{c,t+1})]$ note that we can re-write the compound Poisson process as $D_{t+1} = N_{t+1}\mu_c - \lambda_t \mu_c$, where N_{t+1} is a Poisson random variable with intensity, conditional on information at time t, equal to $\lambda_t = \ell_0 + \ell_1 w_t$. Therefore, for a scalar τ,

$$\begin{aligned}
E_t[\exp(\tau D_{t+1})] &= E_t[\exp(\tau \mu_c N_{t+1} - \tau \lambda_t \mu_c)] \\
&= \exp[\lambda_t (e^{\tau u_c} - 1) - \tau \lambda_t \mu_c] \\
&= \exp[\lambda_t (\Phi(\tau) - 1)] = \exp[\ell_0 (\Phi(\tau) - 1) + \ell_1 (\Phi(\tau) - 1)(w_t - \mu_w)]
\end{aligned}$$

where we define $\Phi(\tau) = \exp(\tau \mu_c) - \tau \mu_c$. Note that to go from the first to the second line we use the definition of the moment generating function of a Poisson process, $E_t[\exp(\tau N_{t+1})] = \exp[\lambda_t (e^\tau - 1)]$, and the last expressions results from replacing the definition of λ_t. Using these last results, evaluating the expectation (31) and taking logs of both sides results in the following equation:

$$\begin{aligned}
0 &= \ln \delta + \left(1 - \frac{1}{\psi}\right) \mu + \kappa_0 + A_0 (1 - \kappa_1) + \kappa_1 \sigma^2 (1-\nu) A_\sigma + \kappa_1 A_w (1 - \rho_w) \mu_w \\
&+ \frac{\theta}{2} (\kappa_1 A_\sigma)^2 \sigma_v^2 + \frac{1}{\theta} (\ell_0 - \ell_1 \mu_w) [\Phi((1-\gamma)\varphi_c + \theta \kappa_1 A_x \varphi_x) - 1] + \frac{\theta}{2} (\kappa_1 A_x \tau_w + \kappa_1 A_w)^2 \sigma_\zeta^2 \\
&+ \left[\left(1 - \frac{1}{\psi}\right) + \kappa_1 A_w \tau_x - A_x (1 - \kappa_1 \rho)\right] x_t \\
&+ \left\{A_\sigma (\kappa_1 \nu - 1) + \frac{1}{2} \theta \left[\left(1 - \frac{1}{\psi}\right)^2 + (\kappa_1 A_x \varphi_e)^2\right]\right\} \sigma_t^2 \\
&+ \left[A_w (\kappa_1 \rho_w - 1) + \frac{1}{\theta} \ell_1 \left[\Phi((1-\gamma)\varphi_c + \theta \kappa_1 A_x \varphi_x) - 1\right]\right] w_t
\end{aligned}$$

This equation must hold for all values the state variables take, therefore, the terms multiplying the state variables as well as the constant term should equal to zero. Hence, we have that A_x, A_σ, A_w must satisfy,

$$
\begin{aligned}
A_x &= \frac{\left(1-\frac{1}{\psi}\right)+\kappa_1 A_w \tau_x}{1-\kappa_1\rho} && (32)\\
A_\sigma &= \frac{\frac{1}{2}\theta\left[\left(1-\frac{1}{\psi}\right)^2+(\kappa_1 A_x\varphi_e)^2\right]}{1-\kappa_1\nu} && (33)\\
A_w &= \frac{\ell_1\left[\Phi((1-\gamma)\varphi_c+\theta\kappa_1 A_x\varphi_x)-1\right]}{\theta(1-\kappa_1\rho_w)} && (34)
\end{aligned}
$$

and A_0 satisfies,

$$
\begin{aligned}
A_0 &= \Bigg(\ln\delta+\left(1-\frac{1}{\psi}\right)\mu+\kappa_0+\kappa_1\sigma^2(1-\nu)A_\sigma+\kappa_1 A_w(1-\rho_w)\mu_w+\frac{\theta}{2}(\kappa_1 A_\sigma)^2\sigma_v^2\\
&\quad+\frac{(\ell_0-\ell_1\mu_w)[\Phi((1-\gamma)\varphi_c+\theta\kappa_1 A_x\varphi_x)-1]}{\theta}+\frac{\theta}{2}(\kappa_1 A_x\tau_w+\kappa_1 A_w)^2\sigma_\zeta^2\Bigg)/(1-\kappa_1)
\end{aligned}
$$

To obtain solutions for A_0, A_x, A_w, and A_σ we also need to solve for the linearization constants κ_1 and κ_0. The log-linearization constants are given by,

$$
\begin{aligned}
\kappa_0 &= \ln(1+e^{z_c})-\kappa_1 z_c && (35)\\
\kappa_1 &= \frac{e^{z_c}}{1+e^{z_c}} && (36)
\end{aligned}
$$

where $z_c = E(z_{c,t}) = A_0 + A_\sigma\sigma^2 + A_w w$. As can be seen from these expressions, the log-liner coefficients depend on the values of A_0, A_x, A_σ and A_w which also depend on these coefficients. Therefore, these must be solved jointly with the loadings A_0, A_x, A_σ and A_w, since they are endogenous to the model. Manipulating equations (35) and (36) we have:

$$
\begin{aligned}
\kappa_0 &= -\kappa_1\ln\kappa_1-(1-\kappa_1)\ln(1-\kappa_1) && (37)\\
\kappa_0-(1-\kappa_1)A_0 &= -\ln\kappa_1+(1-\kappa_1)A_\sigma\sigma^2+(1-\kappa_1)A_w w && (38)
\end{aligned}
$$

therefore, using (38) we can eliminate κ_0 and A_0 from (35) leading to the following expression that κ_1 must satisfy,

$$\begin{aligned}\ln\kappa_1 &= \ln\delta + \left(1-\frac{1}{\psi}\right)\mu + (1-\kappa_1)A_\sigma\sigma^2 + (1-\kappa_1)A_w w + \kappa_1\sigma^2(1-\nu)A_\sigma \\ &+\kappa_1 A_w(1-\rho_w)\mu_w + \frac{\theta}{2}(\kappa_1 A_\sigma)^2\sigma_v^2 + \frac{(\ell_0-\ell_1\mu_w)[\Phi((1-\gamma)\varphi_c+\theta\kappa_1 A_x\varphi_x)-1]}{\theta} \\ &+\frac{\theta}{2}(\kappa_1 A_x\tau_w + \kappa_1 A_w)^2\sigma_\zeta^2 \end{aligned} \quad (39)$$

Given a starting value for κ_1 we solve for A_x, A_σ and A_w, which we use to iterate on κ_1 in (39) until it converges. Finally, using the solution for κ_1 and A_σ and A_w we can recover κ_0 and A_0 from equations (37) and (38), respectively.

Having solved for the wealth-consumption ratio, we can re-write the log-linear approximation of the return on the consumption claim as follows,

$$\begin{aligned} r_{c,t+1} &= \mu + \kappa_0 - A_0(1-\kappa_1) + \kappa_1 A_\sigma(1-\nu)\sigma^2 + \kappa_1 A_w(1-\rho_w)\mu_w + \frac{1}{\psi}x_t + A_\sigma(\kappa_1\nu-1)\sigma_t^2 \\ &+A_w(\kappa_1\rho_w-1)w_t + \sigma_t\eta_{t+1} + \kappa_1 A_x\varphi_e e_{t+1} + \kappa_1 A_\sigma\sigma_v v_{t+1} + (A_x\tau_w + A_w)\kappa_1\sigma_\zeta\zeta_{t+1} \\ &+(\kappa_1 A_x\varphi_x + \varphi_c)D_{t+1} \end{aligned}$$

Using the solution to the return on wealth $r_{c,t+1}$, the IMRS can be restated in terms of the state variables and the various shocks.

A.2 Solution for the Pricing Kernel and the Risk-Free Rate

The solution to the price-consumption ratio $z_{c,t}$ allows us to express the pricing kernel can be expressed as a function of the state variables and the model parameters,

$$m_{t+1} = m_0 + m_x x_t + m_\sigma\sigma_t^2 + m_w w_t - \lambda_\eta\sigma_t\eta_{t+1} - \lambda_e\sigma_t e_{t+1} - \lambda_v\sigma_v v_{t+1} - \lambda_\zeta\sigma_\zeta\zeta_{t+1} - \lambda_D D_{t+1} \quad (40)$$

with,

$$
\begin{aligned}
m_0 &= \theta \ln \delta - \gamma \mu + (\theta - 1)[\kappa_0 - A_0(1-\kappa_1)] + (\theta-1)\kappa_1 A_w (1-\rho_w)\mu_w \\
&\quad + (\theta-1)\kappa_1 A_\sigma (1-\nu)\sigma^2 \\
m_x &= -\frac{1}{\psi} \\
m_\sigma &= (\theta-1)\kappa_1 A_\sigma (\kappa_1 \nu - 1) \\
m_w &= (\theta-1)\kappa_1 A_w (\kappa_1 \rho_w - 1)
\end{aligned}
$$

and

$$
\begin{aligned}
\lambda_\eta &= \gamma \\
\lambda_e &= (1-\theta)\kappa_1 A_x \varphi_e \\
\lambda_v &= (1-\theta)\kappa_1 A_\sigma \\
\lambda_\zeta &= (1-\theta)\kappa_1 (A_x \tau_w + A_w) \\
\lambda_D &= (1-\theta)\kappa_1 A_x \varphi_x + \gamma \varphi_c
\end{aligned}
$$

To derive the risk-free rate at time t, we use the Euler equation which mandates that $r_{f,t}$ must satisfy,

$$E_t[\exp(m_{t+1} + r_{f,t})] = 1$$

which implies that $\exp(-r_{f,t}) = E_t[\exp(m_{t+1})]$. The expectation can be evaluated using the expression for the IMRS and is equal to,

$$
\begin{aligned}
E_t[\exp(m_{t+1})] &= \exp\Bigg[m_0 + \frac{1}{2}(\lambda_v^2 \sigma_v^2 + \lambda_\zeta^2 \sigma_\zeta^2) + (\ell_0 - \ell_1 w)(\Phi(-\lambda_D) - 1) + m_x x_t \\
&\quad + \Big(m_\sigma + \frac{1}{2}(\lambda_\eta^2 + \lambda_e^2) \Big) \sigma_t^2 + \Big(m_w + \ell_1 (\Phi(-\lambda_D) - 1) \Big) w_t \Bigg]
\end{aligned}
$$

which yields the following expression for the risk-free rate $r_{f,t}$:

$$r_{f,t} = r_f + A_{f,x} x_t + A_{f,\sigma} \sigma_t^2 + A_{f,w} w_t \tag{41}$$

with,

$$\begin{aligned}
r_f &= -m_0 - \frac{1}{2}(\lambda_v^2\sigma_v^2 + \lambda_\zeta^2\sigma_\zeta^2) - (\ell_0 - \ell_1\mu_w)(\Phi(-\lambda_D) - 1) \\
A_{f,x} &= -m_x \\
A_{f,\sigma} &= -m_\sigma - \frac{1}{2}(\lambda_\eta^2 + \lambda_e^2) \\
A_{f,w} &= -m_w - \ell_1(\Phi(-\lambda_D) - 1)
\end{aligned}$$

Using the expression for the return on the consumption claim and the pricing kernel, the risk premium on the consumption claim equals,

$$\begin{aligned}
E_t(r_{c,t+1} - r_{f,t}) + \frac{1}{2}\mathrm{Var}_t(r_{m,t+1}) &= -\mathrm{cov}_t(m_{t+1}, r_{m,t+1}) \\
&= \beta_\eta\lambda_\eta\sigma_t^2 + \beta_x\lambda_e\sigma_t^2 + \beta_v\lambda_v\sigma_v^2 + \beta_w\lambda_\zeta\sigma_\zeta^2 + \beta_D\lambda_D\lambda_t u_c^2
\end{aligned}$$

where the β's are equal to,

$$\begin{aligned}
\beta_\eta &= 1 \\
\beta_x &= \kappa_1 A_x \varphi_e \\
\beta_v &= \kappa_1 A_\sigma \\
\beta_w &= (A_x\tau_w + A_w)\kappa_1 \\
\beta_D &= (\varphi_c + \kappa_1 A_x \varphi_x)
\end{aligned}$$

A.3 Solution for the Consumption Paying Asset exempt from Global Warming Effects

Consider an asset that pays a unit of consumption exempt from the effects of temperature in the economy, therefore, the dividend of this asset grows as follows,

$$\Delta c_{t+1}^* = \mu + x_t^* + \sigma_t\eta_{t+1} \quad (42)$$

$$x_{t+1}^* = x_{t+1} - \tau_w\sigma_\zeta\zeta_{t+1} - \varphi_x D_{t+1} \quad (43)$$

where Δc^*_{t+1} is consumption growth and x^*_{t+1} expected growth abstracting from global warming effects. The log-linear approximation of the return on this asset equals,

$$r_{c^*,t+1} = \kappa^*_0 + \kappa^*_1 z_{c^*,t+1} + \Delta c^*_{t+1} - z_{c^*,t}, \tag{44}$$

where $z_{c^*,t}$ is the (log) price-dividend ratio for this particular asset which has c^*_{t+1} as dividend. The return on this asset must satisfy,

$$E_t[\exp(m_{t+1} + r_{c^*,t+1})] = 1 \tag{45}$$

To solve for the return we conjecture that the solution to the price-dividend ratio is $z_{c^*,t} = A^*_0 + A^*_x x_t + A^*_\sigma \sigma^2_t + A^*_w w_t + A^*_\zeta \sigma_\zeta \zeta_t + A^*_D D_t$. Replacing our conjecture into the Euler equation as well as the expression for the pricing kernel (40) and evaluating the expectations, we obtain the following expressions for the loadings on the price-consumption ratio $z_{c^*,t}$:

$$A^*_x = \frac{\left(1 - \frac{1}{\psi}\right) + \kappa^*_1 A^*_w \tau_x}{1 - \kappa^*_1 \rho} \tag{46}$$

$$A^*_\sigma = \frac{m_\sigma + \frac{1}{2}\left[(\kappa^*_1 A^*_x \varphi_e - \lambda_e)^2 + (1 - \lambda_\eta)^2\right]}{1 - \kappa^*_1 \nu} \tag{47}$$

$$A^*_w = \frac{m_w + \ell_1 \left[\Phi(\kappa^*_1 \varphi_x (1 - A^*_x) - \lambda_D) - 1\right]}{1 - \kappa^*_1 \rho_w} \tag{48}$$

while $A^*_\zeta = -\tau_w$ and $A^*_D = -\varphi_x$.

A.4 Solution for the Dividend Paying Asset

The market return is the return on an asset that pays a dividend which grows at rate Δd_{t+1} described by the following process,

$$\Delta d_{t+1} = \mu_d + \phi x_t + \pi \sigma_t \eta_{t+1} + \phi \varphi_c D_{t+1} + \varphi_u \sigma_t u_{t+1} \tag{49}$$

and the market return must satisfy,

$$E_t(\exp(m_{t+1} + r_{m,t+1})) = 1$$

We conjecture that the price-dividend ratio is affine in the state variables, $z_{m,t} = A_{0,m} + A_{x,m}x_t + A_{\sigma,m}\sigma_t^2 + A_{w,m}w_t$, and to solve for the loadings on each state variables we follow the same procedure used to solve for the wealth-consumption ratio. Therefore, we substitute the market return by its log-linear approximation,

$$r_{m,t+1} = \kappa_{0,m} + \kappa_{1,m}z_{m,t+1} + \Delta d_{t+1} - z_{m,t}$$

which after some algebraic manipulation equals to,

$$\begin{aligned} r_{m,t+1} \;=\;& \kappa_{0,m} - A_{0,m}(1-\kappa_{1,m}) + \mu_d + \kappa_{1,m}A_{\sigma,m}(1-\nu)\sigma^2 + \kappa_{1,m}A_{w,m}(1-\rho_w)\mu_w \\ & [\kappa_{1,m}A_{x,m}\rho - A_{x,m} + \phi + \kappa_{1,m}A_{w,m}\tau_x]x_t + A_{\sigma,m}(\kappa_{1,m}\nu - 1)\sigma_t^2 + A_{w,m}(\kappa_{1,m}\rho_w - 1)w_t \\ & +\phi\sigma_t\eta_{t+1} + \kappa_{1,m}A_{x,m}\varphi_e\sigma_t e_{t+1} + \kappa_{1,m}A_{2,m}\sigma_v v_{t+1} \\ & +[\kappa_{1,m}A_{x,m}\tau_w + \kappa_{1,m}A_{3,m}]\sigma_\zeta\zeta_{t+1} + (\phi\varphi_c + \kappa_{1,m}A_{x,m}\varphi_x)D_{t+1} + \varphi_u\sigma_t u_{t+1} \end{aligned}$$

Replacing this expression and the expression for m_{t+1} into the Euler equation, we find that the loadings on the state variables must satisfy,

$$A_{x,m} = \frac{\left(\phi - \frac{1}{\psi}\right) + \kappa_{1,m}A_{w,m}\tau_x}{1-\kappa_{1,m}\rho} \tag{50}$$

$$A_{\sigma,m} = \frac{(\theta-1)(\kappa_1\nu - 1)A_\sigma + \frac{1}{2}\left[(\kappa_1 A_{x,m}\varphi_e - \lambda_e)^2 + (\pi - \lambda_\eta)^2 + \varphi_u^2\right]}{1-\kappa_{1,m}\nu} \tag{51}$$

$$A_{w,m} = \frac{(\theta-1)(\kappa_1\rho_w - 1)A_w + \ell_1\Big[\Phi[\phi\varphi_c + \kappa_{1,m}A_{x,m}\varphi_x - \lambda_D] - 1\Big]}{\theta(1-\kappa_{1,m}\rho_w)} \tag{52}$$

and $A_{0,m}$ must satisfy,

$$\begin{aligned} A_{0,m} = \Big[& m_0 + \kappa_{0,m} + \kappa_{1,m}A_{w,m}(1-\rho_w)\mu_w + A_{\sigma,m}\kappa_{1,m}\sigma^2(1-\nu) + \mu_d + \frac{1}{2}(A_{\sigma,m}\kappa_{1,m} - \lambda_v)^2\sigma_v^2 \\ & + \frac{1}{2}(\kappa_{1,m}Aw,m + \kappa_{1,m}A_{x,m}\tau_w - \lambda_\zeta)^2\sigma_\zeta^2 + (\ell_0 - \ell_1\mu_w)\big(\Phi(\phi\varphi_c + \kappa_{1,m}A_{x,m}\varphi_x - \lambda_D) - 1\big)\Big]/(1-\kappa_{1,m}) \end{aligned}$$

As in the case for the consumption claim, we need to solve for the approximating constants, $\kappa_{0,m}$ and $\kappa_{1,m}$. Using the expressions for the linearization constants $\kappa_{1,m}$ and

$\kappa_{0,m}$ and the condition for $A_{0,m}$ we have,

$$
\begin{aligned}
\ln \kappa_{1,m} \quad = \quad & m_0 + (1-\kappa_{1,m})A_{\sigma,m}\sigma^2 + (1-\kappa_{1,m})A_{w,m}\mu_w + \kappa_{1,m}A_{w,m}(1-\rho_w)\mu_w \\
& + A_{\sigma,m}\kappa_{1,m}(1-\nu)\sigma^2 + \mu_d + \frac{1}{2}(A_{\sigma,m}\kappa_{1,m} - \lambda_v)^2\sigma_v^2 \\
& + \frac{1}{2}(\kappa_{1,m}A_{w,m} + \kappa_{1,m}A_{x,m}\tau_w - \lambda_\zeta)^2\sigma_\zeta^2 + (\ell_0 - \ell_1\mu_w)\Big[\Phi[\phi\varphi_c + \kappa_{1,m}A_{x,m}\varphi_x - \lambda_D] - 1\Big]
\end{aligned}
$$

As in the case for the consumption claim, we use the same algorithm to solve for $\kappa_{1,m}$, and the states loadings on the solution of the price-dividend ratio $A_{0,m}$, $A_{x,m}$, $A_{\sigma,m}$ and $A_{w,m}$.

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Table I

Summary Statistics

	Mean		**Std. Dev.**		**AC(1)**	
Global Temperature	14.02	(0.05)	0.21	(0.03)	0.87	(0.05)
World GDP Growth	1.91	(0.28)	1.35	(0.14)	0.44	(0.13)
World Consumption Growth	1.84	(0.20)	0.92	(0.10)	0.41	(0.13)
World Market Return	6.83	(2.19)	19.65	(2.59)	-0.22	(0.22)
Risk-Free Rate	1.85	(0.50)	2.18	(0.32)	0.69	(0.06)

Table I presents descriptive statistics for the world GDP and consumption growth, global temperature, the world stock market return, and the risk-free rate. The macroeconomic data are real, in per-capita terms, and sampled on an annual frequency. Global temperature is expressed in degrees Celsius (°C) covering the period 1930 to 2008. GDP data cover the period from 1960 to 2008, and consumption data cover the period from 1960 to 2006. The world market return data cover the period from 1988 to 2009, and the data on the real risk-free rate cover 1950 to 2009. Means and volatilities of growth rates and the market return are expressed in percentage terms. Newey-West standard errors are reported in parenthesis.

Table II

Configuration of Model Parameters

Preferences	δ	γ	ψ			
	0.999	10	1.5			
Consumption	μ	ρ	φ_e	σ	ν	σ_w
	0.0015	0.975	0.036	0.0006	0.999	0.0000028
Dividends	μ_d	ϕ	π	φ_u		
	0.0015	2.5	1.75	5.96		
Temperature	μ_w	ρ_w	τ_x	σ_ζ		
	14.6	0.985	0.0	0.025		
Category 1	τ_w	φ_c	φ_x			
	-0.0018	0	0			
Category 2	τ_w	φ_c	φ_x	ℓ_0	ℓ_1	μ_c
	-0.0018	-1.0	0	1/(1200)	1/(1200)	0.01

Table II reports configuration of investors' preferences and time-series parameters that describe the dynamics of consumption, dividend growth rates, and temperature. The model is calibrated on a monthly basis. The state of the economy is described by,

$$\begin{aligned}
\Delta c_{t+1} &= \mu + x_t + \sigma_t \eta_{t+1} + \varphi_c D_{t+1} \\
x_{t+1} &= \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma_t \varphi_e e_{t+1} + \varphi_x D_{t+1} \\
\sigma_t^2 &= \sigma^2 + \nu(\sigma_t^2 - \bar{\sigma}^2) + \sigma_v v_{t+1} \\
w_{t+1} &= \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \\
\Delta d_{t+1} &= \mu_d + \phi x_t + \pi \sigma_t \eta_{t+1} + \varphi_u \sigma_t u_{t+1} + \phi \varphi_c D_{t+1}
\end{aligned}$$

where $D_{t+1} = \sum_{j=1}^{N_{t+1}} \xi_{j,t+1} - \lambda_t \mu_c$ is a compensated compound Poisson process with intensity $\lambda_t = \ell_0 + \ell_1(w_t - \mu_w)$. The size of the jump $\xi_{j,t+1}$ is constant and equals μ_c.

Table III

Model Implies Dynamics of Growth Rates and Returns

Moment	Data Mean	Data S.E.	Category 1	Category 2
$E[\Delta c]$	1.84	(0.20)	1.83	1.83
$\sigma(\Delta c)$	0.92	(0.10)	2.40	2.40
$AC1(\Delta c)$	0.41	(0.13)	0.43	0.42
$E[w_t]$	14.02	(0.05)	14.59	14.59
$\sigma(w_t)$	0.21	(0.03)	0.14	0.14
$AC1(w_t)$	0.87	(0.05)	0.89	0.89
$E[R_c]$	3.49		3.29	3.29
$\sigma(R_c)$	–		3.72	3.73
$E[R_m]$	6.83	(2.19)	7.05	7.05
$\sigma(R_m)$	19.65	(2.59)	18.87	18.87
$E[R_f]$	1.85	(0.50)	1.14	1.14
$\sigma(R_f)$	2.18	(0.32)	1.04	1.04

Table III reports moments of aggregate consumption (c_t), temperature (w_t) growth rates, the return on the consumption claim (R_c), the return on the market dividend claim (R_m), and the risk-free rate (R_f). Data statistics along with standard deviations (in parentheses) are reported in the first column. The data are real, sampled on an annual frequency, and are expressed in percentage terms. The next two columns present model based statistics based on $12 \times 20,000$ monthly data aggregated to annual observations.

Table IV

Model-Based Dollar Costs of Global Warming

	Model	
	Category 1	Category 2
Loss in World Consumption		
Trillions of US$	1.43	3.18
% of World GDP	2.46%	5.47%
Consumption claim		
$E[P^*/C^*]$	75.015	75.048
$E[R_{c^*}]$	3.2342	3.2336
$E[P/C]$	74.983	74.978
$E[R_c]$	3.2895	3.2889

Table IV reports the cost in dollar terms of a reduction in consumption due to temperature risks. The cost of a reduction in consumption is computed as the difference between the price of a consumption-paying asset with and without the effects of temperature. The price-consumption ratio and return of the consumption claim with temperature risks are denoted P/C and R_c, respectively. The price-consumption ratio and return of the consumption claim without temperature risks in the same economy are denoted P^*/C^* and R_{c^*}, respectively. All reported figures are computed based on $12 \times 20,000$ monthly data aggregated to annual horizon. Returns are expressed in percentage terms.

Table V

Model-Based Welfare Costs of Global Warming

	Model	
	Category 1	Category 2
Welfare Costs of Stabilization	0.78	0.81
Temperature Growth Shock		0.79
Natural Disasters		0.02
Economy with temperature risks		
Risk-premium on consumption claim	2.040	2.041
Price-consumption ratio	74.984	74.978
Economy w/o temperature risks		
Risk-premium on consumption claim	2.032	2.032
Price-consumption ratio	75.182	75.182

Table V reports welfare costs of setting temperature effects to zero and the return as well as the price-consumption ratio of a consumption claim in an economy with and without the risks of temperature. The welfare costs of stabilization represents the fraction of consumption that the representative agent would be willing to give up to avoid the negative effects of global warming. All reported figures are computed based on $12 \times 20,000$ monthly data aggregated to annual horizon. Returns are expressed in percentage terms.

Table VI

Role of LRR and Recursive Preferences

	CRRA–LRR		**EZW–hf**	
	Category 1	Category 2	Category 1	Category 2
Welfare Costs	0.04%	0.04%	0.001%	0.07%
$E[R_f]$	16.756	16.751	1.802	1.801
$\sigma[R_f]$	16.079	16.078	0.000	0.000
$E[R_c - R_f]$	0.676	0.676	0.787	0.787
$E[R_m - R_f]$	1.302	1.303	1.412	1.415

Table VI presents model based welfare costs, the risk-free rate and risk premia assuming (i) CRRA–LRR, that preferences are described by a CRRA utility function, i.e. $\gamma = \frac{1}{\psi}$ but otherwise maintain the LRR specification, and (ii) EZW-hf recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty and letting consumption be *iid*, thus temperature innovations and natural disasters impact its high frequency component. R_c is the return on the consumption claim, R_f the risk-free rate, and R_m is the return on the market dividend claim. All reported figures are computed based on $12 \times 20,000$ monthly data aggregated to annual horizon.

Figure I

Temperature Impact on Asset Prices for IES

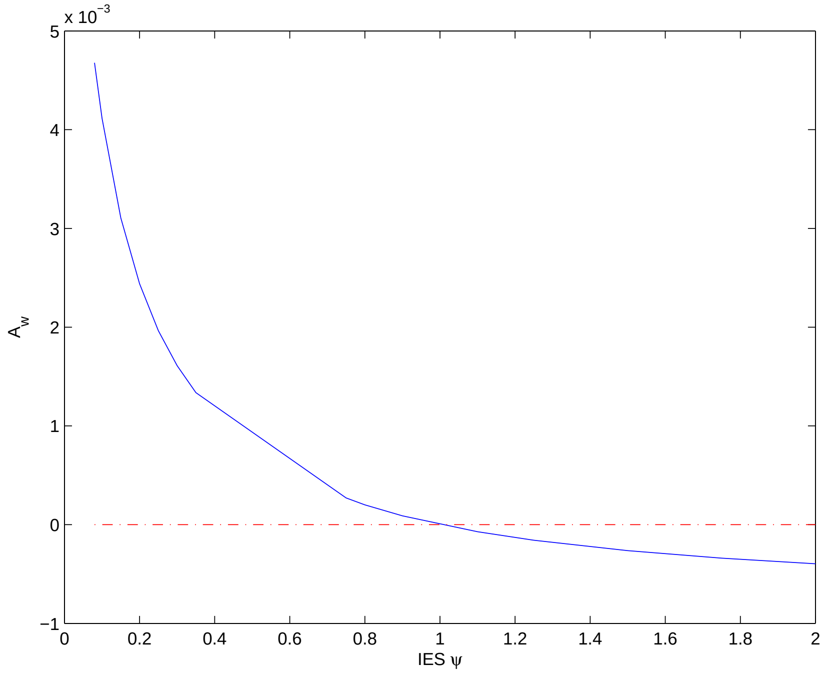

Figure I plots the elasticity of the price-consumption ratio to temperature, A_w, at different values of the IES and setting the risk aversion parameter equal to 10. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ).

Figure II

Temperature Risk at Different Values of the IES

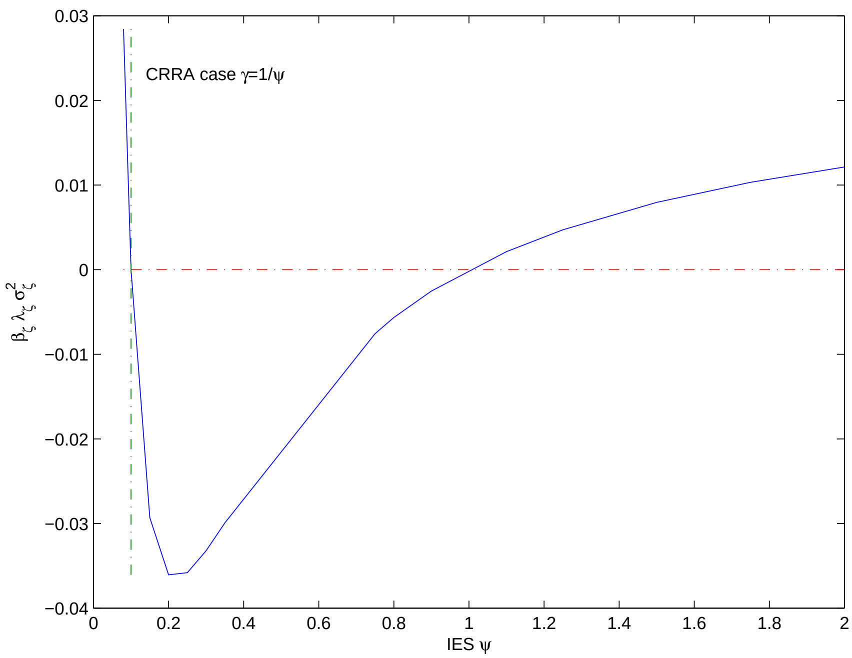

Figure II plots the temperature beta, and the contribution of temperature innovations to the risk premia at different values of the IES and setting the risk aversion parameter equal to 10. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ). The the compensation to temperature innovations, $\beta_\zeta \lambda_\zeta$, is expressed in annual percentage terms.

Figure III
Global Growth and Temperature

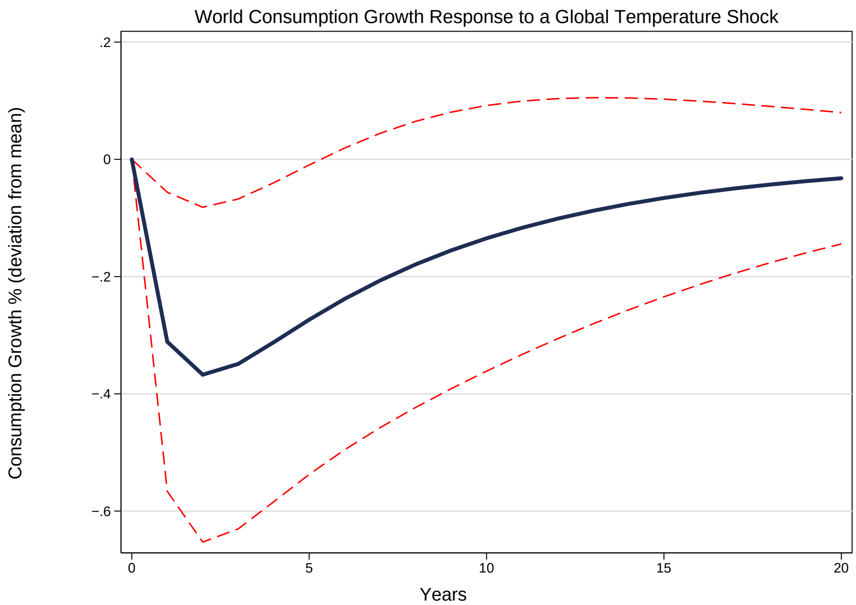

Figure III presents the impulse-response function from a bivariate VAR of world consumption growth and global temperature. The figure depicts the response of consumption growth to a one standard deviation shock to temperature (solid line) along with 95% confidence bands (dashed lines). The data on world consumption is real and covers the period 1960-2007.

Figure IV

Model Implications for Growth and Temperature

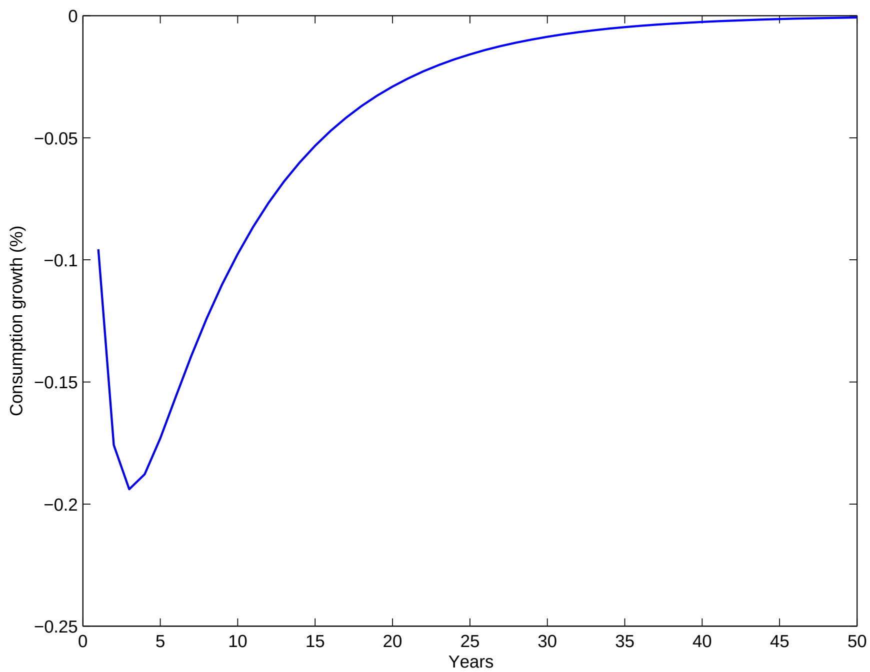

Figure IV presents the response of consumption growth to a one standard deviation shock to temperature implies by a bivariate VAR model. The VAR is estimated using $12 \times 20,000$ monthly data aggregated to annual observations on consumption growth and temperature.