Temperature, Aggregate Risk, and Expected Returns

[VERY PRELIMINARY VERSION. PLEASE DO NOT CIRCULATE.]

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Abstract

In this paper we argue that temperature is a source of aggregate economic risk that influences financial markets. Our argument is based on evidence from global capital markets, which shows that the covariance between country equity returns and temperature contains information about the cross-country risk premium; countries closer to the equator (with higher temperatures) carry positive temperature risk premium which decreases as one moves farther away from the equator.. We show that world GDP growth is negatively related to temperature. Moreover, countries close to the equator have larger negative temperature exposure which becomes more positive far from the equator. The differences in temperature betas mirror exposures to aggregate growth rate risk. That is portfolios with larger exposure to risk from aggregate growth also have larger temperature betas and hence larger risk-premium. We provide a Long-Run Risks based model that accounts for differences in country betas and its links to expected returns, and the connection between aggregate growth and temperature risks.

Keywords: Expected Growth, Equity Premium, Global Warming, Long-Run Risks, Temperature

1 Introduction

Given the prospect of rising global temperature, understanding the potential impact of temperature on the macro-economy and financial markets is of considerable importance. In this article we show that temperature is a source of aggregate risk — we provide evidence that temperature raises expected equity returns and through this raises the incremental cost of borrowing in the aggregate economy. Our evidence comes in two forms. First, we show that GDP growth is negatively related to global temperature, suggesting that it can be a source of aggregate risk. Second, we use data on global capital markets and a cross-section of commonly used US stock portfolios and find that the risk-exposure of these returns to temperature shocks, that is their temperature beta, is a highly significant variable in accounting for cross-sectional differences in expected returns. To interpret this evidence, we present a quantitative consumption-based long-run risks model that is consistent with our empirical evidence; portfolios with larger exposure to temperature-related risks also have larger temperature betas and hence larger risk-premium. Our overall analysis implies that temperature raises the cost of capital, and through this channel temperature can adversely affect economic growth and aggregate wealth.

Over the last 80 years, average annual temperature has risen by 0.80°C. The IPCC, the leading inter-governmental agency studying climate change, predicts that over the next 100 years there could be a rise between 2°C and 5°C in global mean temperatures. Based on integrating a wide-range of micro-channels, their analysis and that of others (e.g., Stern (2007), Nordhaus (2008)) concludes that temperature will adversely affect global GDP. The typical integrative micro-channels that are highlighted are temperature's adverse effects on labor productivity, labor supply, crime, human capital, and political stability, among others.[1] This paper presents evidence that there is an aggregate channel, a cost of capital channel, through which temperature can affect the global economy.

Our modeling approach to understand temperature related risks builds on the long-run risks (LRR) model of Bansal and Yaron (2004), who show that the model can jointly

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[1] Impacts on labor productivity are discussed in Huntington (1915), Crocker and Horst (1981), Meese, Kok, Lewis, and Wyon (1982); Curriero, Heiner, Samet, Zeger, Strug, and Patz (2002), Gallup and Sachs (2001) provide evidence on negative impacts on human capital through health; Jacob, Lefgren, and Moretti (2007) provide evidence on crime and social unrest. More recently, Dell, Jones, and Olken (2009b) document higher temperatures have a negative impact on agriculture, innovation, and political stability, and Zivin and Neidell (2010) find large reductions in U.S. labor supply in industries with high exposure to climate

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 — the latter allows for risk-premia fluctuations. In this paper we present a simplified version of the long-run risks temperature (LRR-T) model proposed in Bansal and Ochoa (2009). The model has an important implication, increased exposure to temperature risk raises temperature betas and hence risk premia. We evaluate this implication in the data and find considerable support for it. We highlight the role of early resolution of uncertainty and show that the data evidence reinforces this specification. We calibrate the model to match key financial market features and quantify the effects on expected returns and on aggregate wealth and financial market wealth due to a rise in temperature.

To evaluate the role of temperature as aggregate risk, we use data on global capital markets and US standard book-to-market and size sorted portfolios that are commonly used in the literature (see Fama and French (1988)). We measure the temperature beta by regressing the real returns on the change in temperature. Using data from global capital markets we show that the covariance between country equity returns and temperature contains information about the cross-country risk premium; countries closer to the equator (with higher temperatures) carry a higher temperature risk premium and countries farther away from the equator have a smaller temperature related risk-premium. Similarly, the exposure of high mean return portfolios such as the high book-to-market and and small size is larger than those for low mean portfolios, low book-to-market and large size firms. Consequently, the temperature beta's explain up to 80% of the cross-sectional variation in expected returns and the temperature market price of risk is about 17 basis points per annum. The temperature MPR is quite significant. We show that both the sign of the betas and the estimated market price of risks is consistent with the implications of the LRR-T model. Our evidence does nor preclude other risks channels (like consumption etc.), rather it highlights that temperature risk are important.

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[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 (2009)

Our LRR-T allows us to study the impact of temperature on wealth and price-dividend ratios in an internally consistent manner. In this general equilibrium model, with a preference of early resolution of uncertainty, the return on aggregate wealth rises with temperature shocks and expected growth rates declines with it — this lowers the wealth-consumption ratio. For our quantitative analysis, we model temperature and consumption as a bivariate process, which is calibrated to match the data — the specification captures the negative impact of temperature on expected growth, as documented in our empirical results. The calibration of preferences and other parameters is standard in the LRR literature. With this we are able to match key asset market data-dimensions, such as, the low risk-free rate, high equity premium, and the volatility of equity and real rates. We find that temperature positively contributes to the risk premia. A higher the exposure of equity to long-run risks translates into a higher exposure to temperature-related risks, and hence to a higher risk premia, as found in the data.

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 document the key empirical regularities. Section 4 describes the calibration of the economy and preference parameters, model implications, and results. Conclusion follows.

2 Long-Run Risks Temperature Model

2.1 Preferences

In this economy, markets are complete and the representative agent has Epstein and Zin (1989) and Weil (1990) type of recursive preferences. The 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, $0 < \delta < 1$ describes the agent's time preferences, γ is the coefficient of risk aversion, $\theta = \frac{1-\gamma}{1-\frac{1}{\psi}}$, and ψ is the intertemporal elasticity of substitution (IES). In this model setup 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, $\gamma = \frac{1}{\psi}$ and $\theta = 1$, 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.

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

$$m_{t+1} = \theta \ln \delta - \frac{\theta}{\psi} \Delta c_{t+1} + (\theta - 1) r_{c,t+1} \tag{2}$$

where $\Delta c_{t+1} = \ln(C_{t+1}/C_t)$ is the growth rate of log consumption, $r_{c,t+1} = \ln(R_{c,t})$ is the continuous return on all invested wealth. This return is different from 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. Furthermore, the standard asset pricing restriction for any asset with continuous return equal to $r_{j,t+1}$ equals,

$$E_t[\exp(m_{t+1} + r_{j,t+1})] = 1 \tag{3}$$

which also holds for the return on the consumption claim $r_{c,t+1}$.

2.2 Consumption Growth and Temperature Dynamics

As is standard in the LLR model, we assume that conditional expected consumption growth contains a small but persistent component x_t. Temperature, labeled as w_t, affects the aggregate consumption dynamics via adversely affecting long-run expected growth:

$$\begin{aligned}
\Delta c_{t+1} &= \mu_c + x_t + \sigma \eta_{t+1} && (4)\\
x_{t+1} &= \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma \varphi_e e_{t+1} && (5)\\
w_{t+1} &= \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} && (6)\\
\Delta d_{t+1} &= \mu_d + \phi x_t + \pi \sigma \eta_{t+1} + \varphi_u \sigma u_{t+1} && (7)
\end{aligned}$$

where all shocks, η_{t+1}, e_{t+1}, ζ_{t+1}, and u_{t+1}, are assumed to be independent standard Normal random variables. As in Bansal and Yaron (2004), μ_c is the unconditional mean of consumption growth, η_{t+1} captures short-run risks, while x_t is a small but persistent component that captures long-run risks in consumption growth. In our setup $\tau_w < 0$ implies a negative impact of temperature shocks on long-run expected growth –this is the key mechanism through which temperature shocks lower long-run expected growth. To capture the feature that growth raises temperature, we allow expected growth rate to affect temperature setting $\tau_x > 0$. 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}. Persistence in temperature is determined by ρ_w and the volatility of temperature innovations is governed by σ_ζ. Dividends have a levered exposure to the persistent component in consumption, x_t, which is captured by the parameter ϕ. In addition, we allow the consumption shock η_{t+1} to influence the dividend process, and thus serve as an additional source of risk premia. The magnitude of this influence is governed by the parameter π.

2.3 Temperature, Risk Prices, and Risk Premia

To characterize the market price of risk as well as the risk premia we first need to characterize the IMRS, given in equation (2). We start by solving for the unobservable return on wealth $r_{c,t+1}$ (the return on the consumption claim), which we approximate using the log-linearization of returns as proposed in Bansal, Kiku, and Yaron (2007).

The log-linear approximation for the continuous return on the wealth portfolio is given by,

$$r_{c,t+1} = \kappa_0 + \kappa_1 z_{c,t+1} + \Delta c_{t+1} - z_{c,t}, \tag{8}$$

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_0 and κ_1 are log linearization constants which depend on the mean of the price-consumption ration. Using the standard asset pricing restriction (3) and the dynamics of consumption we can show that the solution for the price-consumption ratio is affine in the state variables,

$$z_{c,t} = A_0 + A_x x_t \tag{9}$$

where A_x must satisfy,[3]

$$A_x = \frac{1 - \frac{1}{\psi}}{1 - \kappa_1 \rho} \tag{10}$$

The elasticity of the price-consumption ratio with respect to expected growth, x_t, depends on the preference configuration. As discussed in Bansal and Yaron (2004), higher expected growth raises asset valuations and the price to consumption ratio only when the IES is larger than one. Therefore, a positive temperature innovation will lower the price to consumption ratio and asset valuations by A_x times $\tau_w \sigma_\zeta \zeta_{t+1}$, i.e., the impact of temperature shock on expected growth, only when the IES is larger than one.

Given the solution for the return on wealth, the IMRS (2) can be expressed as an affine function of the state variables and innovations of the economy,

$$m_{t+1} = m_0 + m_x x_t - \lambda_\eta \sigma \eta_{t+1} - \lambda_e \sigma e_{t+1} - \lambda_\zeta \sigma_\zeta \zeta_{t+1} \tag{11}$$

where the loadings on expected growth m_x as well as m_0 depend on the model and preference parameters, and are provided in Appendix A.

There are three sources of risk in this economy and the magnitude of the risk compensation for each source of risk depends on their respective market prices of risk, λ. As in the standard LRR framework, λ_η, and λ_e are the market prices for the short-run, and long-run risks. In our setup, innovations on temperature are also priced, λ_ζ. Each of these market prices of risk depend on the underlying preference and model parameters, namely,

$$\begin{aligned}
\lambda_\eta &= \gamma \\
\lambda_e &= (1-\theta)\kappa_1 A_x \varphi_e \\
\lambda_\zeta &= (1-\theta)\kappa_1 A_x \tau_w
\end{aligned}$$

In the case of CRRA preferences, where the risk aversion coefficient equals the inverse of the IES $\gamma = \frac{1}{\psi}$, long-run risks, and temperature risks carry a zero risk compensation. In this case, only short-run risks are priced. When agents are not indifferent about the timing of the resolution of uncertainty in the economy, long-run, and temperature-related risks are also priced.

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[3] The expression for A_0 is presented in Appendix A along with further details about the solution.

Given the expression for the IMRS (11), the risk premium on any asset with continuous return $r_{j,t+1}$ is given by,

$$E_t\left(r_{j,t+1} - r_{f,t} + \frac{1}{2}V_t(r_{j,t+1})\right) = \beta_{j,\eta}\lambda_\eta\sigma^2 + \beta_{j,x}\lambda_e\sigma^2 + \beta_{j,\zeta}\lambda_\zeta\sigma_\zeta^2 \tag{12}$$

where $r_{f,t}$ is the risk-free rate, $\beta_{j,\eta}$, and $\beta_{j,x}$ are the betas of the asset return with respect to the short-run risk η_t, and the long-run risk e_t innovations, respectively. In our framework, the exposure of assets to temperature is determined by the beta of temperature innovations, $\beta_{j,\zeta}$. Then, the risk compensation from each source of risk is determined by the product of the exposure of the asset to that risk, β, and the market price of that risk, λ.

Analogous to the market prices of risk, all asset betas are endogenous to the model and depend on preferences and model dynamics. In particular, the betas for the asset that pays consumption as dividend depend on the elasticity of the price-consumption ratio with respect to expected growth, A_x.[4] The risk compensation for temperature innovation risks will be positive only when agents have a preference for early resolution of uncertainty and the IES is larger than one. Figure I depicts the temperature beta, $\beta_{c,\zeta}$, along with the risk compensation of temperature innovations for different values of the IES and a risk aversion parameter equal to 5. 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.[5]

Another important feature of equation (12) is that a higher exposure to the persistent component in consumption, x_t, rises the risk compensation to temperature shocks. In particular, consider the dividend paying asset with levered exposure to long-run expected growth (7). Figure II plots the contribution of temperature shocks to the risk premia for different values of the dividend exposure to long-run growth assuming that agents

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[4] The exact expressions for the beta's are provided in Appendix A.

[5] Note that when the IES is lower than the CRRA case, the risk premium on temperature innovations is positive, however, this region generates implausible asset prices.

have preferences for early resolution of uncertainty. A higher exposure to temperature risks increases the temperature beta (in absolute value) leading to an increase in the risk compensation from this source of risk.

3 Temperature Risk, Economic Growth, and Expected Equity Returns

3.1 Data

In our empirical exercise we test whether temperature and shocks to temperature have a negative impact on economic growth, and if, as suggested by our model, this negative impact translates into positive contribution of temperature to risk premia. We also test if temperature might have a different impact on countries that are closer to the Equator (with higher temperatures) than countries that are located farther from the Equator.

In our estimations we use macroeconomic data on real GDP per capita for a sample of 143 countries covering the period form 1950 to 2007 from Heston, Summers, and Aten (2009). Data on world real GDP and world private consumption come from the World Bank Development Indicators and cover the period 1960-2008. To compute the distance from the Equator of each country in our sample we use the latitude in degrees of each country compiled by Hall and Jones (1999).[6]

Data on global temperature time series data covering the period 1930–2008 are obtained from the Intergovernmental Panel on Climate Change Data Distribution Center and comes from the Climate Research Unit (IPCC (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).[7] Annual data corresponds to the average of monthly observations.

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[6] The latitude of each country was correspond to the center of the county or province within a country that contains the largest number of people.

[7] To compute large-scale spatial means, each station is associated to a grid point of a 5° × 5° latitude-longitude grid, and monthly temperature anomalies are computed by averaging station anomaly values for all months. Finally, 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.

We compute the market equity return on a sample of 40 countries using the S&P equity index and MSCI equity index expressed in US dollars. We also consider the MSCI All Country World Index which measures equity returns across developed and emerging markets, 45 countries in total, to compute the world market equity return. The sample coverage of these indices vary by country. For each country in our sample we consider the index that has the largest sample, and for countries to be included we select those that have at least 20 years of data. The data on market return for the US corresponds to the return of the NYSE/AMEX/NASDAQ from CRSP. Real returns for all countries are obtained adjusting for US inflation.

We also consider data on US portfolios sorted by size and book-to-market which come from Kenneth French's data library for the period 1930–2008. We use annual data on ten sorted book-to-market portfolios, which are formed based on the book equity to market equity at the end of June of each year using NYSE breakpoints. We also use 2×3 portfolios which are the intersections of 2 portfolios formed on size (market equity) and 3 portfolios formed on the ratio of book equity to market equity ratio. The size breakpoint is the median NYSE market equity and the book-to-market breakpoints are the 30th and 70th NYSE percentiles. For each portfolio, we use annual value weighted returns that we convert to real using the personal consumption expenditures deflator from the NIPA tables.

Table I presents summary statistics for temperature dynamics, annual world GDP and consumption per capita growth for the period 1960-2008. 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 last two rows of Table I present summary statistics for the world market real equity return from 1988 to 2008 and the risk-free rate for the 1950-2008 period. The world market return is 5.48% on average, and the market return volatility equals 19%. The real risk-free rate averages 1.45% per annum, and its volatility is 2.03%, one-tenth of that of equity.

The first two columns of Table VI present descriptive statistics for the market equity return on a sample of 40 developed and emerging countries as well as the world market equity return. The sample varies by country, but all countries have at least twenty years of data. The table in Appendix B lists the countries included in our sample of 143 countries grouped according to their distance from the Equator. We compute the distance from the

Equator for each country in our sample as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1. Then, the first group is comprised by countries that are closer to the Equator, and countries in group 4 are those that are farthest from the Equator. The first two columns of Table IX present descriptive statistics for the ten sorted book-to-market portfolios, six size and book-to-market sorted portfolios, and the market portfolio. The highest book-to-market firms (BM10) have an average real return of 13.37%, while the lowest book-to-market firms (BM1) have an average return of 6.71%, suggesting a book-to-market spread of about 6.7%.

3.2 Empirical Findings

3.2.1 Temperature and Growth

In this section we explore the relationship between temperature and economic growth. We start by examining the unconditional correlation between real world consumption, real world GDP growth and the change in temperature at different horizons. Table II presents the correlation coefficients between growth rates and temperature changes at different horizons using overlapping data covering the period from 1960 to 2008. For both, consumption and GDP growth, the correlation coefficient increases in absolute terms from a near-zero correlation at the one-year horizon to a strong negative correlation at the ten-year horizon. At a 1-year horizon the correlation between consumption growth and changes in temperature is close to zero (0.02), while the correlation coefficient between ten-year growth in consumption and ten-year changes in temperature equals -0.63, and is statistically different from zero. We can give two alternative interpretations to the negative correlation between growth rates and temperature; either a surge in economic growth lowers temperature variations or higher temperature variations lead to lower economic growth. The former interpretation seems implausible, so we interpret this evidence as a negative impact of temperature fluctuations on economic growth.

To quantify the impact of temperature on economic growth, we explore the effect of global temperature as well as temperature shocks on GDP growth in a sample of 143 countries between 1950 and 2007. In particular, we consider a dynamic fixed effects model of the form,

$$\Delta y_{i,t} = \rho \Delta y_{i,t-1} + \alpha_1 w_{t-1} + \alpha_2 \zeta_t + \varsigma_i + \varepsilon_{i,t} \tag{13}$$

where ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance. The dependent variable is real GDP or consumption growth per capita; the left-hand variables include lagged global temperature, w_{t-1}, and temperature shocks, ζ_t, both normalized standardized. This last explanatory variable is constructed as the residual from a first-order autoregressive model of temperature; therefore it is interpreted as a temperature shock.

The first column of Table IV presents the estimation results from a regression of growth on standardized temperature, standardized temperature shocks, and a lag of the dependent variable. The results show that GDP growth is adversely affected by higher levels of temperature as well as temperature shocks. Both coefficients, on lagged temperature and on temperature shocks, are negative and statistically significant. Our estimates suggest that a one standard deviation shock to temperature lowers GDP growth by 0.24%. Moreover, an increase in global temperature of about 0.2°C, one standard deviation, reduces GDP growth by 0.16%. These results indicate that temperature not only has a contemporaneous short-lived impact on economic growth, but its negative impacts tend to persist over time. The second column of Table III presents the results of running a similar regression as in (13) but using as dependent variable world GDP growth. Similar to the panel data evidence, temperature negatively impacts world economic growth. The coefficient on lagged temperature is negative and statistically significant, while temperature shocks have a negative impact on world GDP growth, but its impact is not statistically significant.

Since world GDP is explained to a great extent by developed economies, the negative and statistically significant impact of temperature shocks using a panel of countries suggests that the short-run exposure to temperature shocks might vary across countries. In particular, we explore if countries closer to the Equator (with higher temperatures) have a higher exposure to temperature shocks. The regression presented in second column of Table IV includes as an independent variable the interaction of temperature shocks and the distance from the Equator to our baseline model (13). While the coefficients on lagged temperature and lagged temperature shocks remain negative and statistically significant, the coefficient on the interacted variable is positive and statistically different from zero. Therefore, temperature shocks have a larger negative impact on countries closer to the Equator than countries farther away from the Equator. To further quantify the impact of temperature shocks we group the countries in our sample by their distance from the equator, as presented in Appendix B, in four groups, and interact temperature shocks with the group dummies. Table III shows a one standard deviation shock temperature reduces GDP growth by 0.4% in countries closer to the Equator (Group 1), while it has an effect close to zero in countries farther away from the Equator (Group 4). The impact of temperature shocks is statistically different between countries closer and further from the Equator.

Using a cross-country panel data and temperature in each country, Dell, Jones, and Olken (2009a) also come to the conclusion that temperature lowers growth rates, particularly in emerging economies. There are several candidate channels through which temperature has an impact on economic activity. Higher temperatures have a negative impact on labor productivity (Huntington (1915), Crocker and Horst (1981), Meese, Kok, Lewis, and Wyon (1982)), human capital through health (Curriero, Heiner, Samet, Zeger, Strug, and Patz (2002), Gallup and Sachs (2001)), crime and social unrest (Jacob, Lefgren, and Moretti (2007)). More recently, Dell, Jones, and Olken (2009b) document higher temperatures have a negative impact on agriculture, innovation, and political stability, and Zivin and Neidell (2010) find large reductions in U.S. labor supply in industries with high exposure to climate – all of which can potentially lower economic growth.

Since world GDP has a negative exposure to temperature, we would expect that countries closer to the Equator have higher exposure to risk from aggregate growth. Following Bansal, Dittmar, and Lundblad (2005) explore if countries closer to the Equator have a higher exposure to long-run aggregate growth. Table V presents the results from regressing the GDP growth rate on a trailing average of lagged world GDP growth, and this variable interacted with the distance from a country to the Equator. Irrespective of the number of periods we use to obtain the average, the sign on world GDP growth is positive and statistically significant. Moreover, the interacted variable is negative and statistically significant, implying that countries closer to the Equator have a higher exposure to long-run aggregate growth than countries further form the Equator.

3.2.2 Temperature and Risk Premia

According to our theoretical model, a negative impact of temperature on growth implies a negative exposure of equity market returns to temperature shocks. In particular, we consider the following specification for any asset j market return,

$$E(R_{j,t}) = \lambda_0 + \beta_{j,w}\lambda_w \tag{14}$$

where $R_{j,t}$ is the arithmetic return, $\beta_{j,w}$ is asset's j exposure to temperature shocks, and λ_w is the market price of temperature risks. In this section we examine the exposure to temperature innovations of real market returns from a sample of 40 countries, and the return on 16 characteristic sorted portfolios from the US. In line with our findings in the previous section, we also examine if the variation in temperature betas across countries can be explained by the distance of the country from the equator, reflecting differences in exposure to temperature risks.

Following the standard cross-sectional regression techniques, we compute country j corresponding beta by running a time-series regression of the asset real arithmetic return on temperature change,

$$R_{j,t+1} = \beta_{j,0} + \beta_{j,w}(w_{t+1} - w_t) + \epsilon_{t+1} \tag{15}$$

where ϵ_{t+1} is the error term. Then, we use the estimates of beta for each country and perform a cross-section regression of the average return on the estimated beta, and compute the estimated market price of risk, λ_ζ, using equation (14).

Figure IV presents a scatter plot of the estimated temperature betas against the distance to the Equator for a sample of 40 countries. From the scatter plot we see that, on average, the temperature beta is more negative in countries near the Equator, and becomes more positive as we move away from the Equator. Indeed, the projection coefficient of the distance of the country from the equator on the temperature beta is positive and statistically different from zero. In Table VII we directly compute the temperature beta using a pooled sample of 40 countries. In particular, we estimate a fixed-effects model of the real market return on the change in temperature, and the change in temperature interacted with the distance from the Equator. Again, the coefficient accompanying temperature change is negative and statistically significant, and the coefficient on the interaction term is positive and statistically different from zero. The estimated coefficients imply that the temperature beta is negative in countries at the Equator but decreases in absolute value for countries that are farther from the equator. Using the same group categories as in the growth regressions, we group the countries in our sample according to their distance from the Equator, and interact the temperature change with each group dummy. From the coefficients in Table VII we can compute the temperature beta implied by the estimated coefficients for each of the four categories. Countries closer to the Equator show a negative temperature beta, while for countries further from the Equator the temperature beta decreases becoming even positive.

From our model perspective, the empirical evidence presented in Table VII suggests that countries closer to the Equator have a larger exposure to temperature and long-run growth, which is consistent with the evidence presented in the previous section.

Table VIII presents the results from a cross-section regression of the average market return on the estimated beta for the country market returns. The first column presents the cross-section regression using the estimated temperature betas country-by-country, and the second column use the temperature betas predicted by the model presented in column (2) of Table VII. In both cases, the price of temperature risks is negative and statistically significant. From our model perspective, a negative market price of temperature risks arises when agents have a preference for early resolution of uncertainty and the IES is larger than one, which is the configuration employed in the LRR literature (e.g., Bansal and Yaron (2004)). Since the estimated beta is more negative for countries closer to the equator, the risk premium arising from temperature-related risks is larger in these countries than countries farther from the equator. Figure IV plots the estimated beta against the average market return grouping countries according to their distance from the Equator. Whether we use a grouping of 4 or 8 eight categories, countries with more negative betas (i.e., closer to the Equator) have a higher average return than countries with low or positive betas (i.e., further from the Equator). Figure V plots the predicted expected returns against the average realized returns implied by the cross-sectional regression and the temperature betas obtained country-by-country. The cross-sectional R^2 is 0.43 suggesting that temperature risks can explain an important part of the cross-sectional variation.

We now explore the exposure of US characteristics sorted portfolios to temperature-related risks. Table IX presents the estimated temperature betas using ten sorted book-to-market portfolios, six portfolios sorted by size and book-to-market, and the market portfolio for the US. Remarkably, the estimated beta in all portfolios has a negative sign and is higher (in absolute value) for portfolios with a high book-to-market equity than portfolios with lower book-to-market equity ratio. Consistent with our theoretical model implications, when agents have preference for early resolution of uncertainty we expect the beta across all portfolios to be negative. Similarly, the feature that the estimated beta becomes more negative as we move from low book-to-market portfolios to high book-to-market portfolios implies that exposure to temperature-related risks is higher for firms with high book-to-market equity ratio. Note that small firms have more exposure to temperature risks, as well as firms with high book-to-market portfolio within each size.

Table X presents the results regressing average the market return on US characteristic sorted portfolios and the estimated temperature beta. As in the international evidence, the market price of temperature risks is negative and statistically different from zero. The R^2 for the cross-sectional regression of the average return on 10 portfolios sorted by book-to-market is equal to 0.95, implying that temperature successfully explains the cross-sectional variation in average returns. Since the estimated beta and market price of risk are both negative, temperature has a positive contribution to risk premia. Therefore, as suggested by our theoretical results, the risk premium in value firms is higher, to some extent, because these firms are more highly exposed to temperature risks. This result is consistent with the empirical evidence presented in Bansal, Dittmar, and Lundblad (2005) who find that value firms have a higher exposure to long-run growth. We explore further the ability of temperature explaining the cross-section of average returns including to the cross-sectional regressions the market, and six size and book-to-market sorted portfolios. We present this evidence in the Table X and in Figure VI that plots the predicted expected returns against the average realized returns. Again, the estimate of the price of temperature-related risks is negative and statistically significant, and the model explains 81% of the cross-sectional variation in average returns.

4 Model Evidence

4.1 Calibration

Table XI presents the parameter configuration we use to calibrate the model, which we choose in order to match several key statistics of world growth dynamics, and world market return data. We assume that the decision interval of the agent is monthly and our baseline parametrization for preferences for the dynamics of consumption and dividends is very similar to that used in Bansal, Kiku, and Yaron (2007). The subjective discount factor δ equals 0.999, the risk aversion parameter γ and the intertemporal elasticity of substitution ψ are equal to 5 and 2, 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)).

We set the autoregressive coefficient of temperature ρ_w equal to 0.99 and the volatility of temperature equal to 0.025. The impact of expected growth on temperature τ_x is equal to 0.1, consistent with the view that an increase in economic activity positively impacts temperature. On the other hand, we set the impact of temperature innovations on expected growth τ_w equal to -0.007. These choices allow us to match the unconditional correlation at short and long-horizons between consumption growth and changes in temperature across various horizons. As in Bansal, Kiku, and Yaron (2007), we capture the persistence, volatility, and auto-correlations of consumption growth by calibrating the persistence of expected growth ρ, as well as φ_e and σ (see Table XI).

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.

4.2 Results

Our calibration of the model is chosen to match the bivariate dynamics of consumption and temperature quite well. Table XII presents the model implications for the consumption growth and temperature dynamics. In particular, our calibration is able to account for first-order and higher order autocorrelations of consumption growth. In all of our specifications the first-order autocorrelation of consumption is around 0.48, which is very close to the data. The temperature dynamics implied the model is similar to that observed in the data. The first-order autocorrelation is 0.92, and its volatility 0.17. The model also captures the negative correlation between changes in temperature and consumption growth for different horizons. The correlation is much stronger when we consider the ten-year change in consumption growth rate and the ten-year change in consumption, as implied by the data. At a 1-year horizon, the correlation coefficient is around -0.05 while at a ten-year horizon the correlation coefficient population value equals -0.14, somewhat lower than the data. The model also generates moments of the risk-free rate and market return as well as an equity premium consistent with the data. The risk-free rate is 1.57% with a volatility of 0.93%. On the other hand, the return on the equity claim is higher and more volatile. The expected market return is 5.27%, with a volatility equal to 20.91%.

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 market return beta and the market price of temperature-related risks, we find that temperature risks account for 79 basis points of the total equity premium. Moreover, 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. The temperature beta implied by the model is negative, and around -0.10, which is very close to the temperature beta estimated for the world data (-0.12).

5 Conclusions

In this paper we argue that temperature may be a source of aggregate economic risk. First, we explore whether global temperature and shocks to global temperature have a negative impact on economic growth. Our results show that a one standard deviation shock to temperature lowers GDP growth by 0.24%. When we group countries based to their distance from the Equator, we find that the impact of temperature shocks is larger in countries that are closer to the Equator; a one standard deviation temperature shock reduces GDP growth by 0.4% in countries closer to the Equator, while it has an effect close to zero in countries farther away from the Equator. Even though temperature has a negative contemporaneous effect only in countries close to the Equator, it has a medium- to long-run negative impact on economic growth across all countries.

Consistent with the evidence on the impact of temperature on economic growth, using data from global capital markets we also show that the covariance between country equity returns and temperature contains information about the cross-country risk premium; countries closer to the equator (with higher temperatures) carry a higher temperature risk premium and countries farther away from the equator have a smaller temperature related risk-premium. Even within US, equity portfolios have different exposures to temperature risks which lines up with their expected returns. The differences in temperature-betas mirror exposures to aggregate growth rate risk. That is portfolios with larger exposure to risk from aggregate growth also have larger temperature betas and hence larger risk-premium. This evidence is consistent with temperature having negative aggregate growth impact. We provide a LRR based model that accounts for differences in country betas and its links to expected returns.

References

Bansal, Ravi, Robert F. Dittmar, and Christian T. Lundblad, 2005, Consumption, dividends, and the cross section of equity returns, *The Journal of Finance* 60, 1639–1672.

Bansal, Ravi, Dana Kiku, and Amir Yaron, 2007, Risks for the long run: Estimation and inference, *Manuscript, Department of Economics, Duke University, Durham NC.*

Bansal, Ravi, and Marcelo Ochoa, 2009, Temperature, growth, and asset prices, Working Paper.

Bansal, Ravi, and Amir Yaron, 2004, Risks for the long run: A potential resolution of asset pricing puzzles, *The Journal of Finance* 59, 1481–1509.

Bhamra, Harjoat S., Lars A. Kuehn, and Ilya A. Strebulaev, 2009, The levered equity risk premium and credit spreads: A unified framework, *Review of Financial Studies.*

Crocker, Thomas D., and Robert L. Horst, 1981, Hours of work, labor productivity, and environmental conditions: A case study, *The Review of Economics and Statistics* 63, 361–368.

Curriero, F.C., K.S. Heiner, J.M. Samet, S.L. Zeger, L. Strug, and J.A. Patz, 2002, Temperature and mortality in 11 cities of the eastern united states, *American Journal of Epidemiology* 155, 80.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken, 2009a, Climate shocks and economic growth: Evidence from the last half century, *NBER Working Paper* 14132.

———, 2009b, Temperature and income: Reconciling new cross-sectional and panel estimates, *American Economic Review* 99, 198–204.

Drechsler, Itamar, and Amir. Yaron, 2009, What's vol got to do with it, Working Paper.

Epstein, Larry G., and Stanley E. Zin, 1989, Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A theoretical framework, *Econometrica* pp. 937–969.

Fama, Eugene, and Kenneth French, 1988, Dividend yields and expected stock returns, *Journal of Financial Economics* 22, 3–27.

Gallup, J.L., and J.D. Sachs, 2001, The economic burden of malaria, *American Journal of Tropical Medicine and Hygiene* 64, 85–96.

Hall, Robert E., and Charles I. Jones, 1999, Why do some countries produce so much more output per worker than others?, *The Quarterly Journal of Economics*.

Hansen, L.P., J.C. Heaton, and N. Li, 2008, Consumption strikes back? measuring long-run risk, *Journal of Political Economy* 116, 260–302.

Heston, Alan, Robert Summers, and Bettina Aten, 2009, Penn world table version 6.3, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

Huntington, E., 1915, *Civilization and climate* (Yale University Press).

IPCC, 2007, *Synthesis Report - Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge).

Jacob, B., L. Lefgren, and E. Moretti, 2007, The dynamics of criminal behavior: Evidence from weather shocks, *Journal of Human Resources* 42, 489.

Meese, G., R. Kok, M. Lewis, and D. Wyon, 1982, Effects of moderate cold and heat stress on factory workers in southern africa, *South Africa Journal of Science* 78, 189–197.

Nordhaus, William, 2008, *A Question of Balance: Economic Modeling of Global Warming* (Yale University Press).

Piazzesi, Monika, and Martin Schneider, 2007, Equilibrium yield curves, *in Daron Acemoglu, Kenneth Rogoff, and Michael Woodford, (eds.) NBER Macroeconomics Annual 2006.*

Stern, Nicholas, 2007, *The Economics of Climate Change* (Cambridge University Press, Cambridge, UK).

Weil, Philippe, 1990, Nonexpected utility in macroeconomics, *The Quarterly Journal of Economics* 105, 29–42.

Zivin, Joshua Graff, and Matthew J. Neidell, 2010, Temperature and the allocation of time: Implicationf for climate change, NBER Working Paper 15717.

A Model Solution

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

$$\Delta c_{t+1} = \mu_c + x_t + \sigma \eta_{t+1} \tag{16}$$

$$x_{t+1} = \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma \varphi_e e_{t+1} \tag{17}$$

$$w_{t+1} = \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \tag{18}$$

where η_{t+1}, e_{t+1}, and ζ_{t+1} are independent standard Normal innovations.

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 (2) and the log-linear approximation of the return on the consumption claim asset (8) we have,

$$E_t[\exp(m_{t+1} + r_{c,t+1})] = E_t\left[\exp\left(\theta \ln \delta + \theta\left(1 - \frac{1}{\psi}\right)\Delta c_{t+1} + \theta\kappa_0 + \theta\kappa_1 z_{c,t+1} - \theta z_{c,t}\right)\right] \tag{19}$$

Assuming that the solution for the price-consumption ratio is affine in the state variable, $z_{c,t} = A_0 + A_x x_t$, and replacing Δc_{t+1} we have that,

$$\begin{aligned} m_{t+1} + r_{c,t+1} &= \theta \ln \delta + \theta\left(1 - \frac{1}{\psi}\right)\mu_c + \theta\kappa_0 + \theta A_0(1 - \kappa_1) + \theta\left[\left(1 - \frac{1}{\psi}\right) - A_x(1 - \kappa_1\rho)\right]x_t \\ &\quad + \theta\left(1 - \frac{1}{\psi}\right)\sigma\eta_{t+1} + \theta\kappa_1 A_x \varphi_e \sigma e_{t+1} + \theta\kappa_1 A_x \tau_w \sigma_\zeta \zeta_{t+1} \end{aligned}$$

Using this expression we evaluate the expectation (19) and take logs of both sides to obtain the following equation:

$$\begin{aligned}0 &= \ln\delta + \left(1-\frac{1}{\psi}\right)\mu_c + \kappa_0 + A_0(1-\kappa_1) + \frac{\theta}{2}(\kappa_1 A_x \tau_w)^2\sigma_\zeta^2 \\ &\quad + \left[\left(1-\frac{1}{\psi}\right) - A_x(1-\kappa_1\rho)\right]x_t + \frac{\theta}{2}\left[\left(1-\frac{1}{\psi}\right)^2 + (\kappa_1 A_x \varphi_e)^2\right]\sigma^2\end{aligned}$$

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 must satisfy,

$$A_x = \frac{1-\frac{1}{\psi}}{1-\kappa_1\rho} \tag{20}$$

and A_0 satisfies,

$$A_0 = \left(\ln\delta + \left(1-\frac{1}{\psi}\right)\mu_c + \kappa_0 + \frac{\theta}{2}\left[\left(1-\frac{1}{\psi}\right)^2 + (\kappa_1 A_x\varphi_e)^2\right]\sigma^2 + \frac{\theta}{2}(\kappa_1 A_x\tau_w)^2\sigma_\zeta^2\right)/(1-\kappa_1)$$

To obtain solutions for A_0, and A_x we also need to solve for the linearization constants κ_1 and κ_0, which are given by,

$$\begin{aligned}\kappa_0 &= \ln\left(1+e^{z_c}\right) - \kappa_1 z_c && (21)\\ \kappa_1 &= \frac{e^{z_c}}{1+e^{z_c}} && (22)\end{aligned}$$

where $z_c = E(z_{c,t}) = A_0$. As can be seen from these expressions, the log-liner coefficients depend on A_0 which also depends on these coefficients. Therefore, these must be solved jointly with the loadings A_0, and A_x, since they are endogenous to the model. Manipulating equations (21) and (22) we have:

$$\begin{aligned}\kappa_0 &= -\kappa_1\ln\kappa_1 - (1-\kappa_1)\ln(1-\kappa_1) && (23)\\ \kappa_0 - (1-\kappa_1)A_0 &= -\ln\kappa_1 && (24)\end{aligned}$$

therefore, using (24) we can eliminate κ_0 and A_0 from (A.1). Given a starting value for κ_1 we solve for A_x, which we use to iterate on κ_1 until it converges. Finally, using the solution for κ_1 we can recover κ_0 and A_0 from equations (23) and (24), 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,

$$\begin{aligned} r_{c,t+1} &= \mu_c + \kappa_0 - A_0(1-\kappa_1) + \frac{\theta}{2}\left[\left(1-\frac{1}{\psi}\right)^2 + (\kappa_1 A_x \varphi_e)^2\right]\sigma^2 + \frac{1}{\psi}x_t \\ &\quad + \sigma\eta_{t+1} + \kappa_1 A_x \varphi_e \sigma e_{t+1} + A_x \tau_w \kappa_1 \sigma_\zeta \zeta_{t+1} \end{aligned} \tag{25}$$

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,

$$m_{t+1} = m_0 + m_x x_t - \lambda_\eta \sigma \eta_{t+1} - \lambda_e \sigma e_{t+1} - \lambda_v \sigma_v v_{t+1} - \lambda_\zeta \sigma_\zeta \zeta_{t+1} \tag{26}$$

with,

$$\begin{aligned} m_0 &= \theta \ln \delta - \gamma\mu + (\theta - 1)[\kappa_0 - A_0(1-\kappa_1)] \\ m_x &= -\frac{1}{\psi} \end{aligned}$$

and

$$\begin{aligned} \lambda_\eta &= \gamma \\ \lambda_e &= (1-\theta)\kappa_1 A_x \varphi_e \\ \lambda_\zeta &= (1-\theta)\kappa_1 A_x \tau_w \end{aligned}$$

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

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

implying that $\exp(-r_{f,t}) = E_t[\exp(m_{t+1})]$. The expectation can be evaluated using the expression for the IMRS and we can obtain the following expression for the risk-free rate

$r_{f,t}$:

$$r_{f,t} = r_f + A_{f,x} x_t \tag{27}$$

with,

$$\begin{aligned} r_f &= -m_0 - \frac{1}{2}(\lambda_n^2 + \lambda_e^2)\sigma^2 - \frac{1}{2}\lambda_\zeta^2 \sigma_z eta^2 & (28) \\ A_{f,x} &= -m_x & (29) \end{aligned}$$

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

$$\begin{aligned} E_t(r_{c,t+1} - r_{f,t}) + \frac{1}{2}\mathrm{Var}_t(r_{m,t+1}) &= -\mathrm{cov}_t(m_{t+1}, r_{m,t+1}) \\ &= \beta_{c,\eta}\lambda_\eta \sigma_t^2 + \beta_{c,e}\lambda_e \sigma_t^2 + \beta_{c,\zeta}\lambda_\zeta \sigma_\zeta^2 \end{aligned}$$

where the β's are equal to,

$$\begin{aligned} \beta_\eta &= 1 \\ \beta_e &= \kappa_1 A_x \varphi_e \\ \beta_\zeta &= A_x \tau_w \kappa_1 \end{aligned}$$

A.3 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,

$$\Delta d_{t+1} = \mu_d + \phi x_t + \pi \sigma \eta_{t+1} + \varphi_u \sigma u_{t+1} \tag{30}$$

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, $z_{m,t} = A_{0,m} + A_{x,m} x_t$, 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,

$$\begin{aligned} r_{m,t+1} &= \kappa_{0,m} - A_{0,m}(1-\kappa_{1,m}) + \mu_d + [\kappa_{1,m} A_{x,m}\rho - A_{x,m} + \phi] x_t + \phi\sigma\eta_{t+1} + \kappa_{1,m} A_{x,m}\varphi_e \sigma e_{t+1} \\ &\quad + \kappa_{1,m} A_{x,m} \sigma_\zeta \zeta_{t+1} + \varphi_u \sigma_t u_{t+1} \end{aligned}$$

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,

$$A_{x,m} = \frac{\phi - \frac{1}{\psi}}{1 - \kappa_{1,m}\rho} \tag{31}$$

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

$$A_{0,m} = \left[m_0 + \kappa_{0,m} + \mu_d + \frac{1}{2}(\kappa_{1,m} A_{x,m} \tau_w - \lambda_\zeta)^2 \sigma_\zeta^2 \right] / (1 - \kappa_{1,m})$$

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

B Countries Grouped by Distance From the Equator

Group 1	Group 2	Group 3	Group 4
Angola	Barbados	Algeria	Austria
Benin	Belize	Argentina	Belgium
Burundi	Bolivia	Australia	Bulgaria
Cameroon	Brazil	Bahamas	Canada
Central Afr.R.	Burkina faso	Bahrain	Denmark
Chad	Cape Verde Is.	Bangladesh	Finland
Colombia	Dominica	Bhutan	France
Comoros	Dominican rep.	Botswana	Germany
Congo	El salvador	Chile	Greece
Costa rica	Fiji	China	Hungary
Djibouti	Gambia	Cyprus	Iceland
Ecuador	Grenada	Egypt	Ireland
Ethiopia	Guatemala	Hong Kong	Italy
Gabon	Guinea-biss	India	Korea, rep.
Ghana	Haiti	Iran	Luxembourg
Guinea	Honduras	Israel	Mongolia
Guyana	Jamaica	Japan	Netherlands
Indonesia	Laos	Jordan	Norway
Ivory Coast	Madagascar	Kuwait	Poland
Kenya	Malawi	Lesotho	Portugal
Malaysia	Mali	Malta	Romania
Nigeria	Mauritania	Mauritius	Spain
Panama	Mexico	Morocco	Sweden
Papua n.guinea	Mozambique	Nepal	Switzerland
Rwanda	Namibia	New zealand	Turkey
Seychelles	Nicaragua	Oman	U.K.
Sierra leone	Niger	Pakistan	
Singapore	Peru	Paraguay	
Solomon is.	Philippines	Qatar	
Somalia	Puerto rico	Saudi arabia	
Sri lanka	Senegal	South africa	
Suriname	St.kitts	Swaziland	
Tanzania	St.lucia	Syria	
Togo	St.vincent	Taiwan	
Trinidad & Tobago	Sudan	Tonga	
Uganda	Thailand	Tunisia	
Venezuela	Vanuatu	U.S.A.	
Zaire	Western samoa	Uruguay	
	Zambia	Vietnam	
	Zimbabwe		

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	5.48	(2.74)	19.08	(2.59)	-0.02	(0.22)
Real Risk-Free Rate	1.45	(0.48)	2.03	(0.43)	0.67	(0.07)

Table I presents descriptive statistics for world GDP and consumption growth, global temperature, 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 2008, and the data on the real risk-free rate cover 1950 to 2008. Means and volatilities of growth rates and the market return are expressed in percentage terms. Newey-West standard errors are reported in in parenthesis.

Table II

Correlation Between Temperature and Growth Rates

	World			
Horizon	GDP		Consumption	
1-year	0.02	(0.14)	0.12	(0.15)
5-years	-0.13	(0.17)	-0.15	(0.14)
10-years	-0.63	(0.14)	-0.65	(0.14)

Table II presents the correlation coefficient between consumption, GDP growth and the change in temperature at different horizons for the world and the US. The correlation coefficient between growth rates and temperature change at the $j-$th horizon equals $\frac{cov(y_{t+j}-y_t, w_{t+j}-w_t)}{\sigma(y_{t+j}-y_t)\sigma(w_{t+j}-w_t)}$ where w_t denotes temperature, and y_t the log of consumption or GDP per capita. World GDP and consumption data are annual, and cover the period from 1960 to 2008 and from 1960 to 2006, respectively. The data for the US is annual covering the period from 1920 to 2008. Newey-West Standard errors are presented in parenthesis.

Table III

Temperature Impact on Growth Rates

	Dependent Variable	
Regressors	GDP	World GDP
AR(1)	0.07	0.40
	(0.03)	(0.12)
Lagged Temperature	-0.16	-0.25
	(0.09)	(0.18)
Temp. Residual	-0.24	-0.04
	(0.08)	(0.24)
Observations	6960	47
Countries	143+World	
R-squared	0.07	0.22

Table III presents the results from a regression of growth on standardized temperature, standardized temperature innovations, and lags of the dependent variable. The first column presents the results from a regression using a panel of 143 countries and the world aggregate data using a fixed-effects model. The second column of the table presents the results from a regression of world GDP on temperature and temperature shocks. Growth rates are expressed in percentage terms. Temperature is standardized, thus the coefficient reflects the impact of one standard deviation of temperature on growth rates. Temperature innovations are the residual from regressing temperature on its own lag. The first column reports standard errors corrected for autocorrelation and heteroskedasticity in parenthesis. The second column reports Newey-West standard errors in parenthesis.

Table IV

Temperature, GDP Growth, and Distance from the Equator

	Dep. Var.: *GDP growth*		
Regressor	(1)	(2)	(3)
Lagged GDP growth	0.07	0.07	0.07
	(0.03)	(0.03)	(0.03)
Lagged Temperature	-0.16	-0.16	-0.16
	(0.09)	(0.09)	(0.09)
Temperature Shock	-0.24	-0.42	-0.39
	(0.08)	(0.16)	(0.18)
Temp. Shock × Distance		0.70	
		(0.40)	
Temp. Shock × Group 2			-0.02
			(0.24)
Temp. Shock × Group 3			0.34
			(0.23)
Temp. Shock × Group 4			0.36
			(0.21)
Observations	6960	6913	6913
Number of Countries	143+World	143	143
R-squared	0.07	0.07	0.07

Table IV presents the results from a regression of real GDP growth on standardized temperature, standardized temperature innovations, and a lag of the dependent variable. This table presents the results from a regression using a panel of 143 countries and a fixed-effects model. The sample covers the period from 1950 to 2007. GDP is real and in per capita terms. Growth rates are expressed in percentage terms. Temperature is standardized; thus the coefficient reflects the impact of one standard deviation of temperature on growth rates. Temperature shocks are the residual from regressing temperature on its own lag. The distance from the Equator is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1. Standard errors corrected for autocorrelation and heteroskedasticity are presented in parenthesis.

Table V

Real GDP Growth Exposure to Long-Run World GDP Growth

	Dep. Var.: *Real GDP Growth*		
Regressor	$K = 4$	$K = 6$	$K = 8$
Lagged LR World GDP growth	0.71	0.94	1.03
	(0.15)	(0.20)	(0.23)
Lagged LR World GDP × Distance	-0.77	-1.22	-1.05
	(0.42)	(0.55)	(0.62)
Observations	5956	5845	5512
Number of countries	143	143	143
R-squared	0.073	0.08	0.08

Table V presents the results from a regression of real GDP growth on a measure of long-run world GDP growth, and long-run world GDP growth interacted with the distance from the Equator. The results come from a regression using a panel of 143 countries and a fixed-effects model. The long-run world GDP growth is computed as the trailing K-period moving average; each column presents the regression results for different values of K. Growth rates are expressed in percentage terms. The data is annual and covers the period from 1950 to 2007. Standard errors corrected for autocorrelation and heteroskedasticity are presented in parenthesis.

Table VI

Market Return Across the World

Country	Mean	Std. Dev.	Sample
Argentina	41.59	115.94	1976 – 2008
Australia	8.11	24.81	1971 – 2008
Austria	9.81	38.26	1971 – 2008
Belgium	10.42	28.25	1971 – 2008
Brazil	20.60	56.72	1976 – 2008
Canada	7.16	21.13	1971 – 2008
Chile	26.66	49.87	1976 – 2008
Colombia	29.41	57.81	1985 – 2008
Denmark	12.28	28.95	1971 – 2008
Finland	16.42	51.24	1988 – 2008
France	9.98	28.26	1971 – 2008
Germany	10.21	29.97	1971 – 2008
Greece	15.77	43.47	1988 – 2008
Hong Kong	18.22	45.67	1971 – 2008
India	13.90	35.63	1976 – 2008
Indonesia	25.08	72.54	1988 – 2008
Ireland	6.31	30.20	1988 – 2008
Italy	7.58	35.98	1971 – 2008
Japan	10.56	33.84	1971 – 2008
Jordan	10.70	31.38	1979 – 2008
Korea	16.76	47.39	1976 – 2008
Malaysia	8.30	33.71	1985 – 2008
Mexico	21.09	48.22	1976 – 2008
Netherlands	10.46	20.87	1971 – 2008
New Zealand	5.06	28.99	1988 – 2008
Nigeria	18.66	53.10	1985 – 2008
Norway	13.03	43.39	1971 – 2008
Pakistan	17.41	54.04	1985 – 2008
Philippines	27.90	84.95	1985 – 2008
Portugal	4.91	28.91	1988 – 2008
Singapore	14.22	46.35	1971 – 2008
Spain	10.16	32.03	1971 – 2008
Sweden	13.27	29.09	1971 – 2008
Switzerland	10.21	24.49	1971 – 2008
Taiwan	14.70	46.50	1985 – 2008
Thailand	15.67	49.68	1976 – 2008
Turkey	46.36	139.74	1988 – 2008
United Kingdom	9.60	27.48	1971 – 2008
United States	6.65	18.32	1970 – 2008
Zimbabwe	44.79	170.98	1976 – 2008
World	5.48	19.08	1988 – 2008

Table VI presents descriptive statistics for 40 countries and the world. The first two columns report summary statistics for value weighted equity returns. The third column reports the sample coverage which varies by country, but each country has at least 20 years of data. The market return data are annual, real, and expressed in percentage terms.

Table VII

Temperature Beta and Distance from the Equator

	Dep. Var.: *Real Returns*		
Regressor	(1)	(2)	(3)
Δ Temperature	-0.10	-0.70	-0.48
	(0.12)	(0.28)	(0.39)
Δ Temp × Distance		1.49	
		(0.59)	
Δ Temp. × Group 2			-0.22
			(0.52)
Δ Temp. × Group 3			0.28
			(0.45)
Δ Temp. × Group 4			0.64
			(0.41)
Observations	1268	1268	1268
Number of Countries	40	40	40
R-squared	0.03	0.04	0.04

Table VII reports results from a regression of the real equity return on the change of global temperature, and the change of temperature interacted with the distance from the Equator for an unbalanced panel of 40 countries and a fixed-effects model. The distance from the Equator is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1. Standard errors corrected for autocorrelation and heteroskedasticity are presented in parenthesis. The data on the market real return for each country are annual, real, and the sample coverage varies by country but each country has at least 20 years of data.

Table VIII

Market Price of Temperature Risk

Temperature Beta	λ_0	λ_w	R^2
Country-by-country	0.14	-0.08	0.43
	(0.01)	(0.01)	
Pooled model	0.14	-0.13	0.12
	(0.00)	(0.01)	

Table VIII presents the results from a cross-sectional regression where the average real return is regressed on the estimated temperature beta. The first row presents the coefficients and the adjusted R^2 from a projection of the average real market return from 40 countries and the world market portfolio. The temperature beta is computed regressing the real market return of each country on the change of temperature. The second row presents the same regression, but the temperature beta is computed from the fixed-effects model presented in the second column of Table VII. Standard errors are presented in parenthesis. The data is annual and real. Standard errors are reported in parenthesis.

Table IX

US Portfolio Returns and Temperature Risk

Portfolio	Std. Dev.	Mean	Temp. Beta
BM1	21.54	6.71	-0.25
BM2	18.99	7.84	-0.25
BM3	19.12	7.82	-0.31
BM4	22.26	7.92	-0.27
BM5	22.40	9.19	-0.39
BM6	23.51	9.62	-0.36
BM7	24.86	9.73	-0.41
BM8	26.78	12.06	-0.54
BM9	27.99	12.53	-0.51
BM10	33.13	13.37	-0.62
S1-BML	33.28	9.98	-0.52
S1-BMM	28.52	13.45	-0.50
S1-BMH	31.23	15.78	-0.56
S2-BML	19.74	7.28	-0.26
S2-BMM	21.73	8.47	-0.32
S2-BMH	27.41	11.59	-0.53
Market	20.16	7.84	-0.32

Table IX presents descriptive statistics and the temperature beta for 16 characteristic sorted decile portfolios and the market portfolio. The first two columns present summary statistics for value weighted returns on portfolios formed on book-to-market ratio (BM) and on the intersection of size and book-to-market ratio. BM1 corresponds to the lowest book-to-market decile. S1 represents small firms, and S2 represents large firms. BML, BMM, and BMH correspond to low, medium, and high book-to-equity firms, respectively. The portfolio temperature beta, presented in the last column, is obtained by regressing real returns for each portfolio on the change in northern-hemisphere temperature. The data are annual, cover the period 1930-2008, and are converted to real using the PCE deflator.

Table X

Market Price of Temperature Risk

Temperature Beta	λ_0	λ_w	R^2
10 US portfolios	0.03	-0.17	0.94
	(0.01)	(0.01)	
17 US portfolios	0.02	-0.19	0.81
	(0.01)	(0.02)	

Table X presents the results from a cross-sectional regression where the average real return is regressed on the estimated temperature beta. The first row presents the results from a regression of the average real market return on 10 book-to-market sorted US portfolios on the estimated temperature beta. The last row presents the results from a cross-section regression where the average real return on 17 US portfolios (10 book-to-market sorted portfolios, 6 size and book-to-market sorted portfolios, and the market portfolio) is regressed on the estimated temperature beta. The data is annual and real.

Table XI

Configuration of Model Parameters

Preferences	δ	γ	ψ		
	0.999	5	2.0		
Consumption	μ	ρ	φ_e	σ	τ_w
	0.0015	0.975	0.038	0.008	-0.007
Dividends	μ_d	ϕ	π	φ_u	
	0.0015	3.5	2.0	4.5	
Temperature	μ_w	ρ_w	τ_x	σ_ζ	
	14.0	0.99	0.1	0.025	

Table XI 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,

$$
\begin{aligned}
\Delta c_{t+1} &= \mu_c + x_t + \sigma \eta_{t+1} \\
x_{t+1} &= \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma \varphi_e e_{t+1} \\
w_{t+1} &= \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \\
\Delta d_{t+1} &= \mu_d + \phi x_t + \pi \sigma \eta_{t+1} + \varphi_u \sigma u_{t+1}
\end{aligned}
$$

where η_{t+1}, e_{t+1}, ζ_{t+1}, and u_{t+1} are Gaussian standard innovations.

Table XII

Model Implied Dynamics of Growth Rates and Returns

Moment	Model
$E[\Delta c]$	1.75
$\sigma(\Delta c)$	2.87
$AC1(\Delta c)$	0.48
$E[w_t]$	14.01
$\sigma(w_t)$	0.17
$AC1(w_t)$	0.92
$corr(\Delta c, \Delta w)$	-0.05
$corr(\Delta^5 c, \Delta^5 w)$	-0.12
$corr(\Delta^{10} c, \Delta^{10} w)$	-0.14
$E[R_m]$	5.27
$\sigma(R_m)$	20.91
$E[R_f]$	1.57
$\sigma(R_f)$	0.93

Table XII reports moments of aggregate consumption (c_t), temperature (w_t), and returns of the aggregate stock market. Model based statistics are computed using $12 \times 20,000$ monthly data aggregated to annual horizon. Means and volatilities of returns and growth rates are expressed in percentage terms.

Figure I

Temperature Risk at Different Values of the IES

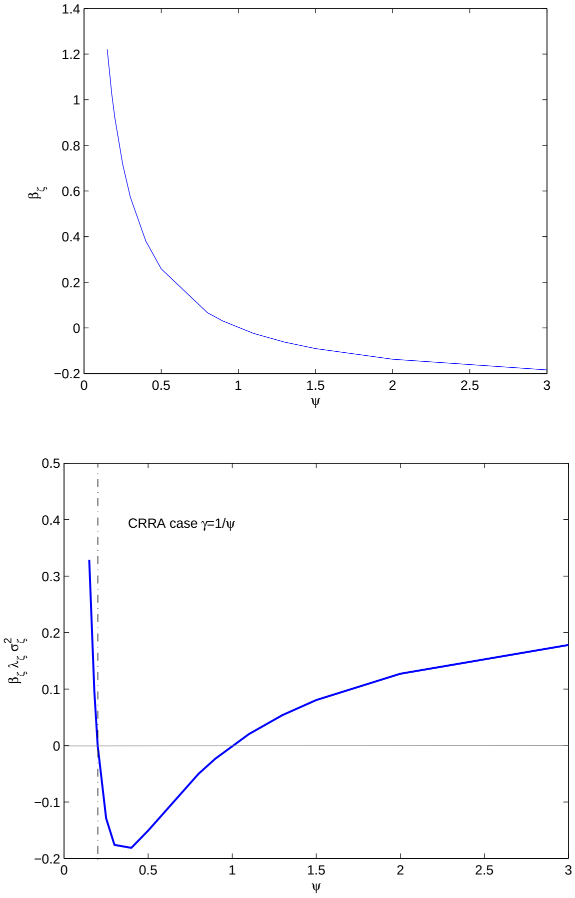


Figure I plots the temperature beta, and the contribution of temperature innovations to the risk premia at different values of the IES and setting the risk aversion parameter equal to 5. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ). The the compensation to temperature innovations, $\beta_\zeta \lambda_\zeta$, is expressed in annual percentage terms.

Figure II

Temperature Risk and Dividend's Exposure to Long-Run Growth

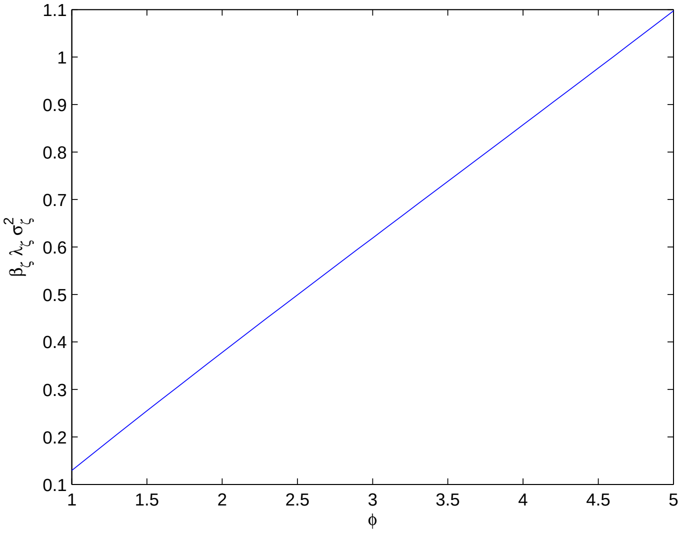


Figure II the contribution of temperature innovations to the risk premia at different values of dividend's exposure to long-run growth, ϕ. The compensation to temperature innovations, $\beta_{\zeta,m}\lambda_\zeta$, is expressed in annual percentage terms.

Figure III

Temperature Beta and Distance from the Equator

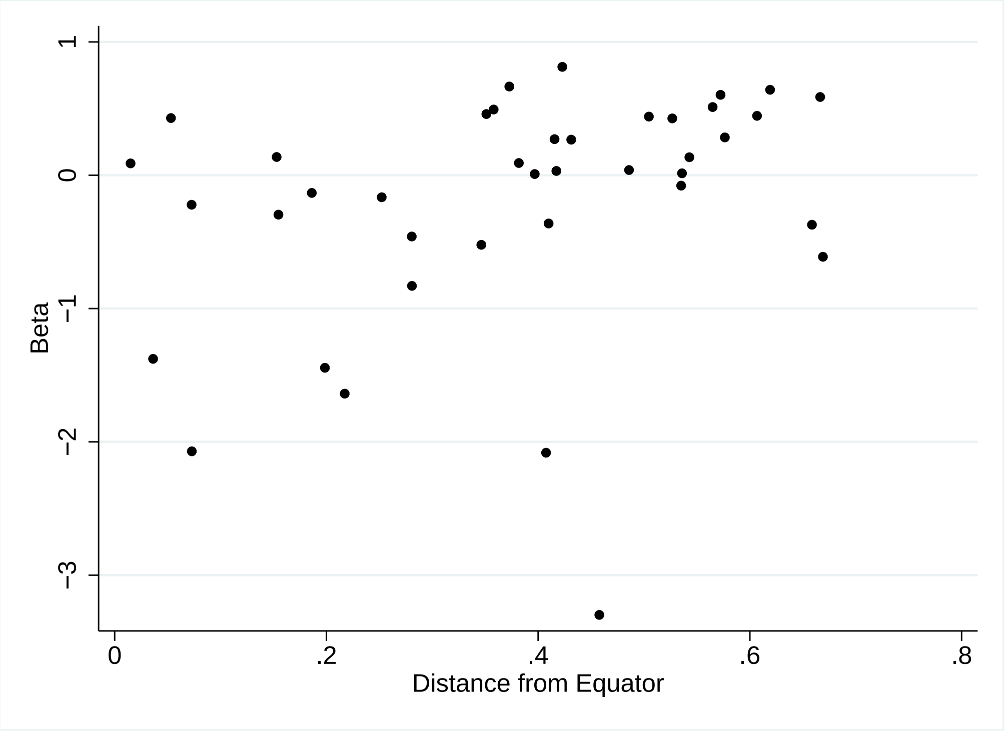
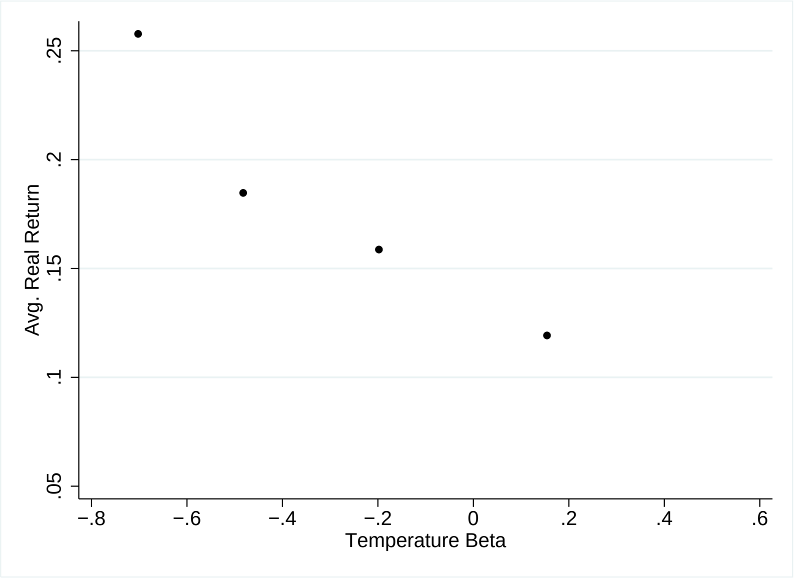


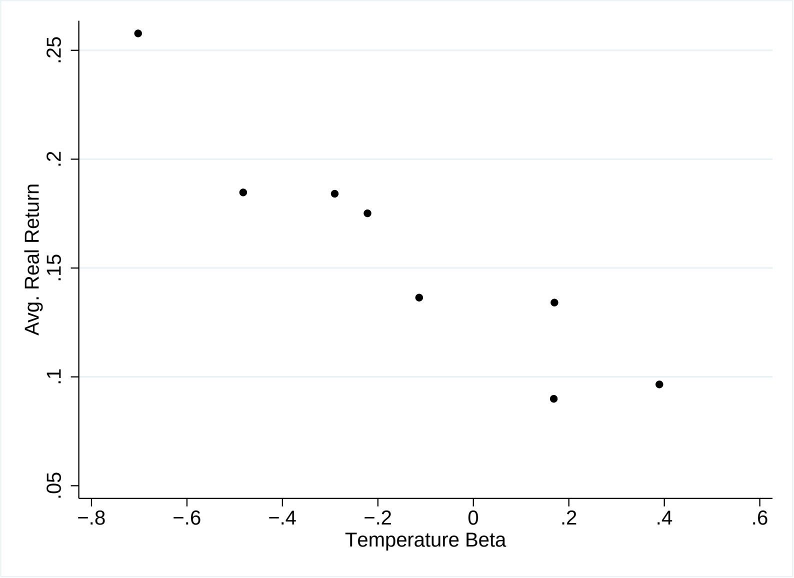
Figure IV presents a scatterplot for estimated temperature beta against the distance to the Equator for a sample of 40 countries. The value of the temperature beta is obtained by regressing the market real return for each country on the change in global temperature. The distance from the equator is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1. The data is annual and the sample varies by country as shown in Table VI.

Figure IV

Temperature Beta and Real Returns



4 group country portfolios



8 group country portfolios

Figure IV presents a scatterplot for mean realized returns against estimated betas for a sample of 40 countries grouped in portfolios according to the country's distance from the Equator. The value of the temperature beta is obtained from the model presented in Table VII where we directly compute the temperature beta grouping countries according to their distance from the Equator. The data on returns is annual, and real.

Figure V

Country Fitted Expected Returns

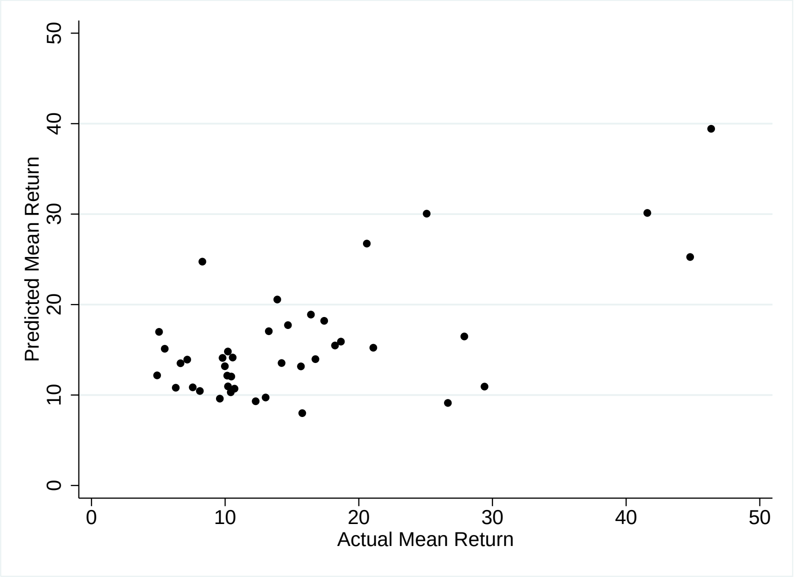


Figure V presents a scatterplot for mean realized returns against estimated betas for a sample of 40 countries grouped in portfolios according to the country's distance from the Equator. The value of the temperature beta is obtained by regressing real returns for each country on the change in global temperature. The data is annual and the sample varies by country as shown in Table VI.

Figure VI

US Portfolios Fitted Expected Returns

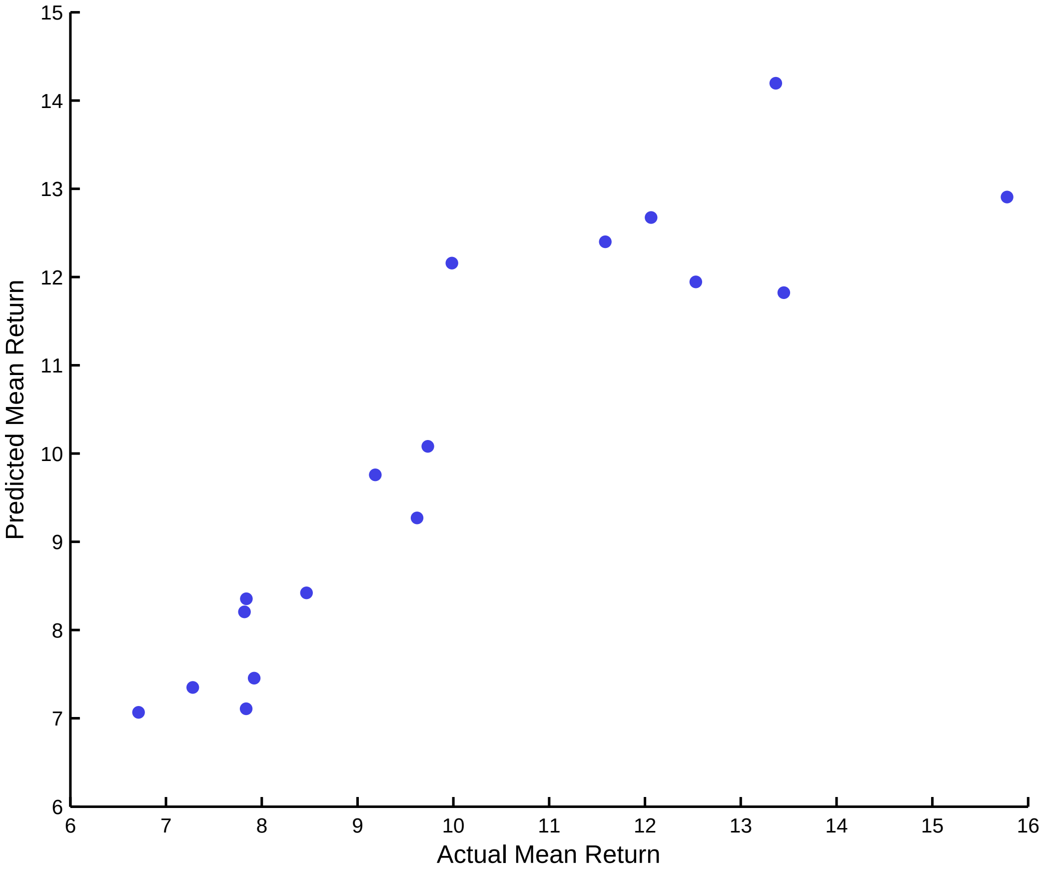


Figure VI presents a scatterplot for the fitted expected returns against mean realized returns using a set of 17 portfolios (10 book-to-market, 3 × 2 size book-to-market, and the market portfolio). The fitted expected returns are a model where we regress the value weighted average return for each portfolio on the estimated. The value of the temperature beta is obtained by regressing real returns for each portfolio on the change in Northern-Hemisphere temperature. The data are annual, cover the period 1929-2008, and are converted to real using a measure of US inflation.