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TEMPERATURE, AGGREGATE RISK, AND EXPECTED RETURNS

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ABSTRACT

In this paper we show that temperature is an aggregate risk factor that adversely affects economic growth. Our argument is based on evidence from global capital markets which shows that the covariance between country equity returns and temperature (i.e., temperature betas) contains sharp information about the cross-country risk premium; countries closer to the Equator carry a positive temperature risk premium which decreases as one moves farther away from the Equator. The differences in temperature betas mirror exposures to aggregate growth rate risk, which we show is negatively impacted by temperature shocks. That is, portfolios with larger exposure to risk from aggregate growth also have larger temperature betas; hence, a larger risk premium. We further show that increases in global temperature have a negative impact on economic growth in countries closer to the Equator, while its impact is negligible in countries at high latitudes. Consistent with this evidence, we show that there is a parallel between a country's distance to the Equator and the economy's dependence on climate sensitive sectors; in countries closer to the Equator industries with a high exposure to temperature are more prevalent. We provide a Long-Run Risks based model that quantitatively accounts for cross-sectional differences in temperature betas, its link to expected returns, and the connection between aggregate growth and temperature risks.

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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 economic risk in global equity markets; we provide evidence that temperature raises expected equity returns and, consequently, rises the cost of borrowing in the aggregate economy. Our evidence comes in two forms. First, using data on global capital markets we find that the risk-exposure of these returns to temperature shocks, i.e., their temperature beta, is a highly significant variable in accounting for cross-sectional differences in expected returns. Second, using a panel of countries we show that GDP growth is negatively related to global temperature, suggesting that temperature can be a source of aggregate risk. To interpret the empirical evidence, we present a quantitative consumption-based long-run risks model that quantitatively accounts for the observed cross-sectional differences in temperature betas, the compensation for temperature risk, and the connection between aggregate growth and temperature risks.

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.

To evaluate the role of temperature as an aggregate risk, we use data on global capital markets and measure the temperature beta by regressing the real return on equity for each country on the change in temperature. Using data from capital markets in 38 countries, we show that the covariance between country equity returns and global temperature contains

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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.

information about the cross-country risk premium; countries closer to the equator carry a higher temperature risk premium and countries farther away from the equator have a smaller temperature related risk-premium. In fact, temperature risks can explain 51% of the cross-sectional variation in expected returns across countries. Our evidence does not preclude other risk channels; rather, it highlights that temperature risks are important.

We also provide evidence that there is a parallel between a country's distance to the Equator and the economy's dependence on climate-sensitive sectors. In particular, countries closer to the Equator rely more heavily on agriculture; a quarter of the GDP in countries closest to the Equator comes from agriculture, while in high-latitude countries agriculture represents less than 5%. Furthermore, we show that the covariance between the market return and the return on a portfolio of industries highly exposed to temperature is higher in countries closer to the Equator, suggesting that in countries closer to the Equator industries with a high exposure to temperature are more prevalent. Therefore, the exposure to temperature highly depends on a country's industry structure.

We further 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 lowers GDP growth by 0.24%. Moreover, our findings show 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 0.43% in countries closer to the Equator, while it has an effect close to zero in countries farther away from the Equator. Similarly, an increase in global temperature of about 0.2°C reduces GDP growth by 0.18%. 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. Furthermore, we find that that temperature has also a negative impact on world consumption and GDP growth. The findings in Dell, Jones, and Olken (2009b) are consistent with our empirical evidence.

Our evidence suggests that the differences in temperature-betas mirror exposures to aggregate growth rate risk. Regressing real GDP growth on a trailing average of lagged world GDP growth for a sample of 147 countries, we find that countries closer to the Equator have a larger exposure to risks from long-run aggregate growth than countries further from the Equator. Since temperature negatively impacts long-run aggregate growth, countries with a higher exposure to aggregate growth also have a higher exposure to temperature, and higher compensation from temperature risks. Similarly, Bansal, Dittmar, and Lundblad (2005), using U.S. characteristic sorted portfolios, show that asset's dividends with higher exposure to aggregate consumption have a higher consumption beta, which explains differences in the cross-section of risk premia.

Our modelling 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 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. In this paper we present a long-run risks temperature (LRR-T) model in which temperature negatively impacts expected growth. Our LRR-T allows us to study the impact of temperature on wealth, price-dividend ratios, and expected returns in an internally consistent manner. For our quantitative analysis, we model temperature and consumption as a bivariate process, which we calibrate to capture the negative impact of temperature on expected growth rates, as documented in our empirical results. The model has an important implication, a higher exposure to long-run aggregate growth translates into a higher (more negative) temperature beta as well as a larger risk premium, and a higher compensation for temperature risks; all of which are consistent with the cross-country evidence.

The rest of the paper is organized as follows. Section 2 documents the key empirical regularities. Section 3 presents the LRR-T model, and discusses its theoretical and quantitative implications for asset markets. Conclusions follow.

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[2] Subsequent work has shown that the model can also explain observed credit spreads, the 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).

2 Temperature Risk, Expected Equity Returns, and Economic Growth

2.1 Data and Summary Statistics

We use time series data on global temperature covering the period 1929–2009 obtained from the Intergovernmental Panel on Climate Change Data Distribution Centre 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).[3] Annual temperature data corresponds to the average of monthly observations.

We compute the market equity return for a sample of 38 countries using the Standard & Poor's (S&P) equity index and the Morgan Stanley Capital International (MSCI) equity index, both expressed in U.S. 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 with the longest sample, and for countries to be included we select those that have at least 20 years of data. 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.

We also consider data on U.S. portfolios sorted by industry. We construct portfolios using the Standard Industrial Classification (SIC) at the two digit level for NYSE/AMEX/NASDAQ firms from CRSP for the period 1930-2009. For each portfolio, we use annual equally weighted returns that we convert to real using the PCE deflator from the NIPA tables.

We also use macroeconomic data on real GDP per capita for a sample of 147 countries covering the period form 1950 to 2007 from Heston, Summers, and Aten (2009) (Penn World

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[3] 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, 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.

Tables). Data on world real GDP come from the World Bank Development Indicators and cover the period 1960-2008. We compute the distance to 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. We obtain each country's latitude in degrees from Hall and Jones (1999).[4] In our empirical results we report estimations grouping countries according to their distance to the Equator. The table in Appendix B lists the 147 countries included in our sample grouped according to their distance to the Equator. Countries for which data on market equity returns are available are marked with an asterisk. We partition the sample of countries in four groups based on distance to the Equator. 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.

Table I presents summary statistics for temperature dynamics, annual world GDP and consumption per capita growth. 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 2009 and the risk-free rate for the 1950-2008 period. The world market return is 6.83% on average, 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.

Table II presents descriptive statistics for the market equity return on a sample of 38 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. Partitioning the sample of countries in four groups based on their distance to the Equator, real equity return in countries closest to the Equator (Group 1) averages 24.96%, and the average volatility in these countries is about 70.01%. On the other hand, in countries furthest from the Equator (Group 4) the average equity return is about 12.54%, and the average volatility of equity returns is around 32.56%. Therefore, countries closest to the Equator have, on average, a higher return on equity than countries furthest from the Equator, about 12%. Similarly, countries closest to the Equator have returns about 2.5 times more volatile than countries

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

furthest away from the Equator.

2.2 Temperature and Risk Premia

In this section we start by computing the contemporaneous covariance between the return on equity and innovations to temperature, i.e., the temperature beta. In particular, we examine how the exposure to temperature innovations of real market returns varies with the distance to the Equator in our sample of 38 countries. Then, we explore whether temperature risk explains the cross-sectional variation in expected returns on different portfolios of stocks across countries. Consider the following specification for any asset i's return,

$$E(R_{i,t}) = \lambda_0 + \beta_{i,w}\lambda_w \tag{1}$$

where $R_{i,t}$ is the arithmetic return, $\beta_{i,w}$ is the asset i's exposure to temperature innovations, and λ_w is the market price of temperature risks. Following the standard cross-sectional regression techniques, we compute asset i's corresponding temperature beta by running a time-series regression of the asset real arithmetic return, $R_{i,t}$, on global temperature change, Δw_t,

$$R_{i,t} = \beta_{i,0} + \beta_{i,w}\Delta w_t + \varepsilon_{i,t} \tag{2}$$

where Δw_t represent innovations to temperature, and ε_{t+1} is an error term. Then, we compute the market price of risk, λ_w, using the cross-sectional risk premia restriction stated in equation (1), that is, performing a cross-sectional regression of the average return on a constant and the estimated temperature beta for each portfolio.

Figure I presents a scatter plot of the estimated temperature betas against the distance to the Equator for 38 countries. From the scatter plot we see that, on average, the temperature beta is more negative in countries closer to the Equator, and becomes more positive as we move away from the Equator. Indeed, the projection coefficient of the distance to the Equator on the temperature beta is positive and statistically different from zero. Alternatively, we compute the temperature beta using the pooled sample of countries by estimating a fixed-effects model of the real market return on the change in temperature, and the change in temperature interacted with the distance to the Equator, namely,

$$R_{i,t} = \varsigma_i + (\beta_0 + \beta_1 \times \ell_i)\Delta w_t + \varepsilon_{i,t} \tag{3}$$

where ℓ_i is country i's distance to the Equator, ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance for country i at time t. Under this specification, the temperature beta for country i is equal to $\beta_0+\beta_1\times\ell_i$. The first column of Table III shows that the coefficient accompanying temperature change β_0 is negative and statistically significant, and the coefficient on the interaction term β_1 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. Similar results emerge when we group the countries in our sample in four group categories according to their distance to the Equator, and interact the temperature change with a group dummy. The second column of Table IV presents the estimated coefficients from the following fixed-effect model,

$$R_{i,t} = \varsigma_i + \left(\beta_0 + \sum_{j=2}^{4} \beta_j \times \mathbf{I}(\ell_i \in g_j)\right) \Delta w_t + \varepsilon_{i,t} \tag{4}$$

where $\mathbf{I}(\cdot)$ is an indicator function, g_j for $j = 1, \ldots, 4$ are intervals which sort countries according to their distance to the Equator, countries with $\ell_i \in g_1$ are those closest to the Equator while countries with $\ell_i \in g_4$ are those furthest from the Equator. The estimated coefficients imply that countries closest to the Equator (group 1) have a temperature beta of about -28.28, while countries furthest from the Equator (group 4) have a temperature beta equal to 37.53. The difference between the temperature betas at low and high latitudes is positive and statistically different from zero.

The results from Table IV also show that countries with high mean returns on equity have more negative betas. This negative relationship implies that the market price of temperature risk is negative; therefore, the risk compensation from temperature risks is larger in countries with more negative betas (closer to the Equator). Table V presents the results from a cross-sectional regression of the average market return on the estimated temperature beta β_w for our sample of 38 countries. The estimated market price of temperature risks λ_w is negative, statistically significant, and equal to -0.083% per annum. The contribution of temperature risks to risk premia equals to $\lambda_w\beta_w$. 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 those farther from the Equator. The cross-sectional adjusted-R^2 is 0.51 suggesting that temperature risks can explain a substantial part of the cross-sectional variation in equity returns.

To verify the robustness of our findings we perform our previous estimations using a time-series of simulated temperature. More precisely, we simulate 1,000 samples of time series observations of global temperature assuming that it follows a first-order autoregressive process. Thereafter, for each simulated time-series, we regress the observed market real return on the simulated change in global temperature using the fixed-effects model (4). Panel A of Table VI presents median of the temperature beta for each of the four groups. In contrast to the empirical evidence presented, the median value of the temperature beta does not correlate with the distance to the Equator. More importantly, the cross-sectional regression presented in Panel B shows a median market price of temperature risks close to zero; therefore, the simulated series is unable to explain the cross-sectional differences in expected returns. In contrast, the data shows that temperature risks are important at explaining the differences in equity returns.

2.3 Distance to the Equator and Temperature Sensitive Sectors

The empirical evidence presented in Section 2.2 suggests that countries closer to the Equator have a higher exposure to temperature. In this section we explore if there is a parallel between a country's distance to the Equator and the economy's dependence on climate-sensitive sectors. First, we investigate the correlation between distance to the Equator with the share of agriculture in GDP, as well as the exposure of the market return to a portfolio of industries highly exposed to temperature and its variation across different latitudes.

As shown in Figure II, countries furthest to the Equator are also countries in which, on average, agriculture represents a smaller share of GDP. Across the 38 countries in our sample, the correlation between distance to the Equator and the average share of agriculture in GDP between 1960 and 2007 is positive and equal to 0.55. On average, a quarter of the GDP in countries closest to the Equator (Group 1) comes from agriculture, while in high-latitude countries (Group 4) agriculture represents only 3% of GDP. Moreover, the correlation of country's temperature beta and the share in agriculture is negative and equals -0.46, implying that countries with lower dependence on agriculture will observe smaller betas, therefore, lower temperature-related risks.

The distance to the Equator is also negatively correlated with the exposure of the market return to a portfolio of temperature-sensitive industries. To compute the covariance between country market returns and returns on temperature-sensitive industries, we construct a portfolio of the four industries most exposed to temperature using returns on industry sorted U.S. portfolios. Figure III presents the estimated temperature beta β_w using nine U.S. portfolios sorted by industry. The four industries with the largest betas (more negative) are construction, manufacturing, transportation and utilities, and agriculture. In these industries, workers are highly exposed to temperature because either work is primarily performed outdoors, or facilities are not climate controlled.[5]

To estimate the exposure of each country's market return to the return on this temperature-sensitive portfolio, we estimate the following regression,

$$ER_{i,t} = \beta_{i,0} + \beta_{i,h} ER_t^H + \varepsilon_{i,t} \tag{5}$$

where $ER_{i,t}$ is country i's market return in excess of the risk-free rate, ER_t^H is the return on the temperature-sensitive portfolio in excess of the market return, $\beta_{i,h}$ is country i's exposure to the temperature-sensitive portfolio. Figure IV shows that the estimated exposure to the temperature-sensitive portfolio $\beta_{i,h}$ and the distance to the Equator are negatively related. The correlation coefficient between the exposure to the temperature-sensitive portfolio and the distance to the Equator is -0.46 and statistically different from zero.

In sum, the evidence presented up to this point suggests that countries closer to the Equator are also countries that rely more heavily on climate-sensitive sectors. Agriculture represents a higher portion of the economy in countries closer to the Equator which makes them vulnerable to fluctuations in temperature. In particular, countries in the low latitudes already start with very high temperatures, therefore, increases in temperature bring temperature to levels that are detrimental for agriculture (IPCC (2007)). Similarly, the covariance between the market return and the return on a portfolio of industries highly exposed to temperature is higher in countries closer to the Equator, suggesting that in countries at low latitudes industries with a high exposure to temperature are more prevalent. Therefore, the exposure to temperature highly depends on a country's industry structure.

2.4 Temperature and Growth

In this section we explore the impact of temperature on output growth, both at country levels as well as the world. In particular, we ask if differences in the exposure of output

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[5] The National Institute of Occupational Safety also considers these industries as highly exposed to climate.

growth to temperature mirrors differences in temperature betas across countries. We also examine the impact temperature on world long-run aggregate growth as well as the exposure of country's economic growth to long-run aggregate growth.

Examining the unconditional correlation between world consumption as well as world GDP growth and the change in global temperature at different horizons, we find a negative and significant correlation at long horizons. Table VII 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 GDP growth and changes in temperature is close to zero (0.02), while the correlation coefficient between ten-year growth in GDP and ten-year changes in temperature equals -0.63, and it 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 aggregate world consumption and GDP 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 147 countries between 1950 and 2007. In particular, we consider a dynamic fixed effects model of the form,

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + \beta_0 \zeta_t + \varepsilon_{i,t} \tag{6}$$

where ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance for country i at time t. The dependent variable is real GDP growth per capita; the right-hand side variables include lagged global temperature, w_{t-1}, and temperature shocks, ζ_t, both 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.[6]

The first column of Table VIII presents the estimation results from a regression of growth on standardized temperature, standardized temperature shocks, and a lag of the

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[6] We select a first-order AR model for temperature dynamics using Schwarz information criteria. We also considered the residual using up to four lags and included lagged world GDP growth and the conclusions remained unchanged.

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 0.18%. 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 VIII presents the results of running a similar regression as in (6) 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 its impact is not statistically significant.

Now we explore if countries closer to the Equator, with more negative temperature betas, have a higher exposure to temperature shocks. The regression presented in the first column of Table IX extends our baseline growth model (6) by adding the interaction between temperature shocks and the distance to the Equator as an explanatory variable, namely,

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + (\beta_0 + \beta_1 \times \ell_i)\zeta_t + \varepsilon_{i,t} \tag{7}$$

where ℓ_i is country i's distance to the Equator; thus,the exposure to temperature shocks is given by the term $\beta_0 + \beta_1 \times \ell_i$. The results show that the coefficients on lagged temperature and temperature shocks remain negative and statistically significant, and the coefficient on the interacted variable is positive and statistically significant. 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 to the equator in four groups, and interact temperature shocks with the group dummies. Table VIII shows that a one standard deviation shock to temperature reduces GDP growth by 0.4% in countries closest 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 at lowest and highest latitudes. Figure V plots the response to a one-standard deviation shock to temperature of GDP growth in Ghana, a country close to the Equator $\ell_i = 0.7$, and Norway, a country at high latitudes $\ell_i = 0.67$. GDP growth in Ghana shows a decline for up to four years. Conversely, a temperature shock has no impact on Norway's GDP growth. In sum, as we move close to the Equator, not only GDP growth is more negatively impacted by temperature variations, but also temperature betas are more negative resulting in a higher compensation from temperature risks. The empirical evidence suggests that the exposure of output growth to temperature mirrors differences in temperature risk compensation across countries.

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. Empirical evidence shows that 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 that 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.

Finally, we examine if differences in temperature-betas mirror exposures to aggregate growth rate risk. Following Bansal, Dittmar, and Lundblad (2005), we explore if countries closer to the Equator have a higher exposure to long-run aggregate growth. Table X 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 of 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. The evidence presented suggests that countries with higher exposure to aggregate growth have also more negative temperature betas, therefore, a larger risk compensation from temperature risks. In a similar exercise Bansal, Dittmar, and Lundblad (2005), using U.S. characteristic sorted portfolios, show that asset's dividends with higher exposure to aggregate consumption have a higher consumption beta, which explains differences in the cross-section of risk premia.

3 Long-Run Risks Temperature Model

In this section we lay out a long-run risks model in which temperature has a negative impact on expected growth, as documented in our empirical results. In this general equilibrium model, we explore the connection between aggregate growth and temperature risks.

3.1 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,

$$V_t = \left[(1-\delta)C_t^{\frac{1-\gamma}{\theta}} + \delta\Big(E_t\big[V_{t+1}^{1-\gamma}\big]\Big)^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}, \tag{8}$$

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),

$$m_{t+1} = \theta \ln \delta - \frac{\theta}{\psi}\Delta c_{t+1} + (\theta - 1) r_{c,t+1} \tag{9}$$

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,

$$E_t[\exp(m_{t+1} + r_{j,t+1})] = 1 \tag{10}$$

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

3.2 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, labelled as w_t, affects the aggregate consumption dynamics via adversely affecting long-run expected growth. Therefore, the state of the economy is described by,

$$\begin{aligned}
\Delta c_{t+1} &= \mu_c + x_t + \sigma\eta_{t+1} && (11)\\
x_{t+1} &= \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma\varphi_e e_{t+1} && (12)\\
w_{t+1} &= \mu_w + \rho_w(w_t - \mu_w) + \sigma_\zeta \zeta_{t+1} && (13)\\
\Delta d_{t+1} &= \mu_d + \phi x_t + \pi\sigma\eta_{t+1} + \varphi_u \sigma u_{t+1} && (14)
\end{aligned}$$

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. 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.[7]

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[7] It is straightforward to allow expected growth to have an impact on temperature, but it will have no effect on the model implications since temperature is not a state variable. We do not follow this route since aggregate growth does not seem to have an impact on temperature on the data.

3.3 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 (9). 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,

$$r_{c,t+1} = \kappa_0 + \kappa_1 z_{c,t+1} + \Delta c_{t+1} - z_{c,t}, \tag{15}$$

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 (10) and the dynamics of consumption, we can show that the solution for the price-consumption ratio is affine in the state variables,

$$z_{c,t} = A_0 + A_x x_t \tag{16}$$

where A_x must satisfy,[8]

$$A_x = \frac{1 - \frac{1}{\psi}}{1 - \kappa_1 \rho} \tag{17}$$

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 (9) can be expressed as an affine function of the state variables and innovations of the economy,

$$m_{t+1} = m_0 + m_x x_t - \lambda_\eta \sigma \eta_{t+1} - \lambda_e \sigma e_{t+1} - \lambda_\zeta \sigma_\zeta \zeta_{t+1} \tag{18}$$

where the loadings on expected growth m_x as well as m_0 depend on the model and preference

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

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, temperature innovations 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 related to long-run growth 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 risks are also priced.

Given the expression for the IMRS (18), the risk premium on any asset with continuous return $r_{j,t+1}$ is given by,

$$E_t\left(r_{j,t+1} - r_{f,t} + \frac{1}{2}V_t(r_{j,t+1})\right) = \beta_{j,\eta}\lambda_\eta\sigma^2 + \beta_{j,x}\lambda_e\sigma^2 + \beta_{j,\zeta}\lambda_\zeta\sigma_\zeta^2 \tag{19}$$

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.[9] The risk compensation for temperature innovation risks will be positive only when agents have a preference for early resolution of uncertainty and

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

the IES is larger than one. Figure VI 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.[10]

Another important feature of equation (19) 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 (14). Figure VII plots the contribution of temperature shocks to the risk premia for different values of the dividend exposure to long-run growth assuming that agents 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.

3.4 Calibration

Table XI presents our baseline parametrization chosen to match the bivariate dynamics of world economic growth and global temperature as well as global equity market returns. We assume that the decision interval of the agent is monthly and our baseline parametrization for preferences 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. In order to match the dynamics of global temperature, we set the autoregressive coefficient of temperature ρ_w equal to 0.99 and the volatility of temperature equal to 0.025. We set the impact of temperature on expected growth τ_w equal to -0.005. These choices allow us

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[10] 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.

to match the impact of temperature innovations and temperature on growth rates as well as the unconditional correlation at short and long-horizons between consumption growth and changes in temperature. 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 order to explore the impact of the exposure to long-run growth on asset prices and, in particular, on the compensation of temperature risks in the LRR-T model, we consider a range of values for ϕ, the exposure of dividends to long-run growth,

$$\Delta d_{i,t+1} = \mu_{i,d} + \phi_i x_t + \pi_i \sigma \eta_{t+1} + \varphi_{i,u} \sigma u_{i,t+1} \tag{20}$$

In particular, we generate 40 portfolios varying ϕ_i uniformly between 0.25 and 7.25. Accordingly, we assume that the growth rate in each economy has a different exposure to long-run aggregate growth, as suggested by the empirical evidence. In particular, we consider that growth in country i is described by $\Delta c_{i,t+1} = \mu_{i,c} + \beta_i x_t + \sigma \eta_{t+1}$. We vary the exposure of consumption growth to aggregate growth between 1 and 2.5. Altogether, we choose these parameters to match the temperature beta and the equity risk premium observed across countries. For all cases, we set π_i and $\varphi_{i,u}$ equal to 8.5 and 2.0, respectively.

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. We report model implied statistics based on $1,000$ simulated samples with 50×12 monthly observations to match the length of the observed data, and we also report population values that correspond to the statistics constructed from $12 \times 20,000$ monthly simulated data aggregated to annual horizon.

3.5 Model Quantitative Implications

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 world consumption growth and global temperature dynamics. In particular, our calibration is able to account for first-order and higher order autocorrelations of consumption growth. The first-order autocorrelation of consumption is around 0.41, which is very close to the data. The temperature dynamics implied by the model is similar to that observed in the data. The median first-order autocorrelation is 0.88, and its volatility 0.14. Our calibration also captures the unconditional correlation between consumption growth and temperature. At a 1-year horizon the correlation coefficient is around -0.03, while at a ten-year horizon the correlation coefficient equals -0.13, somewhat lower than the data. More importantly, our calibration can mirror the estimated coefficients from the regression of economic growth on temperature and temperature innovations. Table XIII reports the coefficients from this regression using using model simulated data. We report both, percentiles of the Monte Carlo distribution as well as population values of the corresponding coefficients. As in the data, lagged temperature has a larger impact than temperature shocks. An increase in temperature of 0.2°C translates into a reduction in economic growth of 0.28% in the next period. The negative impact of temperature as well as the negative correlation between growth rates and temperature at long horizons arises from the fact that temperature shocks impact negatively the expected growth rate of consumption, x_t. If temperature has an impact only on short-run growth, then the coefficient on lagged temperature becomes close to zero, preventing the model from accounting for this feature of the data.

The model also generates moments of the risk-free rate and market return as well as an equity premium consistent with the world market data. The median risk-free rate is 1.56% with a volatility of 0.83%. On the other hand, the return on the equity claim is higher and more volatile. The median market return is 5.75%, with a volatility equal to 18.67%. In our framework, where agents are not indifferent about the timing of uncertainty resolution, temperature risks are priced and contribute to the equity risk premium. Using the market return beta and the market price of temperature risks, we find that temperature risks account for 28 basis points of the total equity premium of 4.04% (see Table XII).

Table XIV presents the temperature beta computed as the slope coefficient from projecting the annual change in temperature onto the annual real return on the levered asset for different levels of exposure to long-run growth. In line with the the cross-country evidence, a higher exposure to the persistent component in consumption also yields a higher (more negative) temperature beta, i.e., larger exposure to temperature risks. In particular, in an economy with a high exposure to aggregate growth $-\phi = 7.25$- the model-implied temperature beta equals -1.07, it decreases to -0.48 in the medium exposure configuration $-\phi = 3.3$-, and it is about -0.07 in a case of low exposure to temperature $-\phi = 0.9$. From the estimated temperature beta for 40 simulated portfolios with varying levels of exposure to aggregate growth we find that the correlation between ϕ and the temperature beta is -0.99. That is, a higher exposure to long-run growth translates into a higher exposure to temperature risks.

Under our model calibration, where agents are not indifferent about the timing of uncertainty, not only the temperature betas increase with the economy's exposure to long-run growth but also the risk compensation for temperature risks. Table XIV presents the risk premium on the levered asset, computed using the expression (19), for parametrizations reflecting different levels of exposure to long-run growth. In an economy with a high exposure of the levered asset to long-run growth $-\phi = 7.25$- the risk premium is about 15.1% of which temperature risks explain 1.71%. A medium exposure to long-run growth $-\phi = 3.3$- translates into a risk premium of 7.29% of which temperature risks explain 58 basis points. A low exposure to the persistent component in consumption $-\phi = 0.90$- translates into a risk premium of 3.62% and temperature risks contribute about 5 basis points. As implied by the cross-country evidence, a higher exposure to long-run growth is accompanied with a higher equity premium and a larger compensation for temperature risks.

Table XV presents the results from a cross-sectional regression of the average annual real return on the levered asset on the estimated temperature beta for 40 simulated portfolios with varying levels of exposure to long-run growth ranging from the high exposure case to the low exposure case. The market price of risk is negative and very close to that estimated in the data. The recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty along with the presence of long-run risks are key to replicate the patterns observed in the data. If preferences were described by a CRRA utility function or the long-run risks were absent, temperature risks would not be priced and the market price of risk as well as the temperature beta would be zero. Moreover, without a preference for early resolution of uncertainty temperature would make a negative contribution to risk premium.

4 Conclusions

In this paper we argue that temperature is a source of aggregate economic risk that adversely affects global growth. 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 carry a higher temperature risk premium and countries farther away from the equator have a smaller temperature risk premium. Temperature risks can explain up to 51% of the cross-sectional variation in mean returns across countries. Our evidence also suggests that the differences in temperature-betas mirror exposures to aggregate growth rate risk.

We further show that global temperature has also a negative impact economic growth which parallels the compensation of temperature risks. Grouping countries by their distance to 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. Consistent with this empirical evidence, we show that there is a parallel between a country's distance to the Equator and the economy's dependence on climate-sensitive sectors; industries with a high exposure to temperature are more prevalent in countries closer to the Equator. Therefore, the exposure to temperature highly depends on a country's industry structure.

We present a Long-Run Risks based model that quantitatively accounts for cross-sectional differences in temperature betas, its link to expected returns, and the connection between aggregate growth and temperature risks. In line with the empirical evidence presented, the differences in temperature-betas mirror exposures to aggregate growth rate risk, which we is negatively impacted by temperature shocks. Therefore, a larger exposure to risk from aggregate growth translates into a higher exposure to temperature; hence, larger temperature betas, and a higher compensation from temperature risks.

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A Model Solution

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

$$\begin{aligned} \Delta c_{t+1} &= \mu_c + x_t + \sigma\eta_{t+1} && (21)\\ x_{t+1} &= \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma\varphi_e e_{t+1} && (22)\\ w_{t+1} &= \mu_w + \rho_w(w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} && (23)\end{aligned}$$

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 (9) and the log-linear approximation of the return on the consumption claim asset (15) we have,

$$E_t[\exp(m_{t+1} + r_{c,t+1})] = E_t\left[\exp\left(\theta \ln\delta + \theta\left(1 - \frac{1}{\psi}\right)\Delta c_{t+1} + \theta\kappa_0 + \theta\kappa_1 z_{c,t+1} - \theta z_{c,t}\right)\right] \quad (24)$$

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 (24) 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,

$$A_x = \frac{1-\frac{1}{\psi}}{1-\kappa_1\rho} \tag{25}$$

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,

$$\begin{aligned} \kappa_0 &= \ln(1+e^{z_c}) - \kappa_1 z_c && (26) \\ \kappa_1 &= \frac{e^{z_c}}{1+e^{z_c}} && (27) \end{aligned}$$

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 (26) and (27) we have:

$$\begin{aligned} \kappa_0 &= -\kappa_1\ln\kappa_1 - (1-\kappa_1)\ln(1-\kappa_1) && (28) \\ \kappa_0 - (1-\kappa_1)A_0 &= -\ln\kappa_1 && (29) \end{aligned}$$

therefore, using (29) 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 (28) and (29), 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,

$$r_{c,t+1} = \mu_c + \kappa_0 - A_0(1-\kappa_1) + \frac{1}{\psi}x_t + \sigma\eta_{t+1} + \kappa_1 A_x \varphi_e \sigma e_{t+1} + A_x \tau_w \kappa_1 \sigma_\zeta \zeta_{t+1} \tag{30}$$

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,

$$m_{t+1} = m_0 + m_x x_t - \lambda_\eta \sigma \eta_{t+1} - \lambda_e \sigma e_{t+1} - \lambda_v \sigma_v v_{t+1} - \lambda_\zeta \sigma_\zeta \zeta_{t+1} \tag{31}$$

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 $r_{f,t}$:

$$r_{f,t} = r_f + A_{f,x} x_t \tag{32}$$

with,

$$\begin{aligned} r_f &= -m_0 - \frac{1}{2}(\lambda_n^2 + \lambda_e^2)\sigma^2 - \frac{1}{2}\lambda_\zeta^2\sigma_\zeta^2 && (33) \\ A_{f,x} &= -m_x && (34) \end{aligned}$$

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

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

where the β's are equal to,

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

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,

$$\Delta d_{t+1} = \mu_d + \phi x_t + \pi\sigma\eta_{t+1} + \varphi_u \sigma u_{t+1} \tag{35}$$

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,

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

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,

$$A_{x,m} = \frac{\phi - \frac{1}{\psi}}{1 - \kappa_{1,m}\rho} \tag{36}$$

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 $A_{x,m}$.

Using the expression for the return on the dividend paying claim and the pricing kernel, the risk premium on the this asset equals,

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

where the β's are equal to,

$$\begin{aligned} \beta_{m,\eta} &= \pi \\ \beta_{m,e} &= \kappa_{1,m} A_{x,m} \varphi_e \\ \beta_{m,\zeta} &= \kappa_{1,m} A_{x,m} \tau_w \end{aligned}$$

B Countries Grouped by Distance to the Equator

Group 1
Angola
Barbados
Belize
Benin
Bolivia
Burkina Faso
Burundi
Cameroon
Cape Verde Islands
Central African Rep.
Chad
Colombia
Comoros
Congo
Costa Rica
Djibouti
Dominica
Ecuador
El Salvador
Ethiopia
Fiji
Gabon
Gambia
Ghana
Grenada
Guatemala
Guinea
Guinea-Bissau
Guyana
Honduras
Indonesia*
Ivory Coast
Kenya
Laos
Liberia
Malawi
Malaysia*
Mali
Mauritania
Mexico*
Namibia
Nicaragua
Niger
Nigeria*
Panama
Papua n.guinea
Peru
Philippines*
Rwanda
Senegal
Seychelles
Sierra Leone
Singapore*
Solomon is.
Somalia
Sri Lanka
St. Kitts
St. Lucia
St. Vincent
Sudan
Suriname
Tanzania
Thailand*
Togo
Trinidad& Tobago
Uganda
Vanuatu
Venezuela
Western Samoa
Zaire
Zambia
Zimbabwe

Group 2
Australia*
Bahamas
Bahrain
Bangladesh
Bhutan
Botswana
Brazil*
China
Dominican rep.
Egypt
Haiti
Hong Kong*
India*
Israel
Jamaica
Jordan*
Kuwait
Lesotho
Madagascar
Mauritius
Mozambique
Nepal
Oman
Pakistan*
Paraguay
Puerto Rico
Qatar
Saudi Arabia
South Africa
Swaziland
Taiwan*
Tonga
United Arab Em.
Vietnam

Group 3
Algeria
Argentina*
Austria*
Bulgaria
Canada*
Chile *
Cyprus
France*
Germany*
Greece*
Hungary
Iran
Iraq
Italy*
Japan*
Korea*
Lebanon
Malta
Mongolia
Morocco
New Zealand*
Portugal*
Romania
Spain*
Switzerland*
Syria
Tunisia
Turkey*
United States*
Uruguay

Group 4
Belgium*
Denmark*
Finland*
Iceland
Ireland*
Luxembourg
Netherlands*
Norway*
Poland
Sweden*
U.K.*

* denotes countries with asset market data.

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

Market Return Across the World

Country	Mean	Std. Dev.	Sample
Argentina	42.23	114.26	1976 – 2009
Australia	9.86	26.82	1971 – 2009
Austria	10.70	38.17	1971 – 2009
Belgium	11.64	28.91	1971 – 2009
Brazil	23.76	58.83	1976 – 2009
Canada	8.44	22.32	1971 – 2009
Chile	28.42	50.16	1976 – 2009
Denmark	12.91	28.83	1971 – 2009
Finland	16.24	50.03	1988 – 2009
France	10.57	28.12	1971 – 2009
Germany	10.61	29.69	1971 – 2009
Greece	16.19	42.46	1988 – 2009
Hong Kong	19.28	45.57	1971 – 2009
India	16.50	38.23	1976 – 2009
Indonesia	29.73	74.07	1988 – 2009
Ireland	6.59	29.49	1988 – 2009
Italy	8.09	35.65	1971 – 2009
Japan	10.45	33.41	1971 – 2009
Jordan	10.18	30.97	1979 – 2009
Korea	18.37	47.61	1976 – 2009
Malaysia	10.04	34.15	1985 – 2009
Mexico	22.12	47.87	1976 – 2009
Netherlands	11.28	21.23	1971 – 2009
New Zealand	7.17	30.00	1988 – 2009
Nigeria	17.01	52.65	1985 – 2009
Norway	14.96	44.48	1971 – 2009
Pakistan	20.30	54.86	1985 – 2009
Philippines	29.49	83.55	1985 – 2009
Portugal	6.56	29.25	1988 – 2009
Singapore	15.75	46.74	1971 – 2009
Spain	11.04	32.09	1971 – 2009
Sweden	14.60	29.90	1971 – 2009
Switzerland	10.62	24.29	1971 – 2009
Taiwan	17.31	47.35	1985 – 2009
Thailand	17.47	50.04	1976 – 2009
Turkey	48.72	136.85	1988 – 2009
United Kingdom	10.46	27.63	1971 – 2009
United States	7.16	18.35	1971 – 2009
World	6.83	19.65	1988 – 2009

Table II presents descriptive statistics for 38 countries and the world equity market return. 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 III

Temperature, Returns, and Distance to the Equator

Dep. Var.: Market Return ($R_{i,t}$)		
Coeff.	(1)	(2)
β_0	-55.1	-28.3
	(26.5)	(22.6)
β_1	135.0	
	(55.0)	
β_2		7.00
		(41.8)
β_3		27.8
		(35.5)
β_4		65.8
		(26.7)
Obs.	1250	1250
Countries	38	38
R^2	0.04	0.04

The first column of Table III presents the results from a regression of the real equity return ($R_{i,t}$) on the change of global temperature (Δw_t) for an unbalanced panel of 38 countries and a fixed-effects model,

$$R_{i,t} = \varsigma_i + (\beta_0 + \beta_1 \times \ell_i)\Delta w_t + \varepsilon_{i,t}$$

where ℓ_i is country i's distance to the Equator, which is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1, ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance for country i at time t. Under this specification, the temperature beta for country i equals $\beta_0 + \beta_1 \times \ell_i$.
The second column presents the estimated coefficients from the following fixed-effect model,

$$R_{i,t} = \varsigma_i + \left(\beta_0 + \sum_{j=2}^{4} \beta_j \times \mathbf{I}(\ell_i \in g_j)\right)\Delta w_t + \varepsilon_{i,t}$$

where $\mathbf{I}(\cdot)$ is an indicator function, g_j for $j = 1, \ldots, 4$ are intervals which sort countries according to their distance to the Equator, countries with $\ell_i \in g_1$ are those closest to the Equator while countries with $\ell_i \in g_4$ are those furthest from the Equator. 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 in expressed percentage terms. The sample coverage varies by country but each country has at least 20 years of data.

Table IV

Country Portfolio Returns and Temperature Beta

Country	ℓ	R	β_w
Group 1	0.10	19.74	-28.28
Group 2	0.30	16.56	-21.28
Group 3	0.45	15.11	-0.45
Group 4	0.62	12.44	37.53

Table IV presents descriptive statistics and the temperature-related betas for four country distance-sorted portfolios. Group 1 corresponds to countries closest to the Equator, and Group 4 corresponds to countries furthest from the Equator. The table reports the average distance to the Equator ℓ, the average temperature w, the average real equity return R, and the temperature beta β_w for the countries in each group. ℓ_i is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1. The average temperature is expressed in degrees Celsius and is computed as the average temperature within each group's countries. The temperature betas β_w are computed from the fixed-effects model presented in Table III. The data is annual, and market equity returns are real and expressed in percentage terms.

Table V

Market Price of Temperature Risk

Beta	λ_0	λ_w	$adj - R^2$
Country-by-country	15.3	-0.083	0.51
	(0.01)	(0.01)	

Table V presents the results from a cross-sectional regression where the average real return is regressed on the estimated temperature beta. The table presents the coefficients from a regression of the average real market return from 38 countries on the estimated temperature beta,

$$\bar{R}_i = \lambda_0 + \lambda_w \beta_{i,w} + \varepsilon_i$$

where the temperature beta $\beta_{w,i}$ for country i is computed regressing country i's real market return on the change of global temperature.

Table VI

Global Portfolios Exposure to Simulated Temperature

Panel A: Temperature Beta

	Data	Null	50%
Group 1	-28.28	0.0	2.17
Group 2	-21.28	0.0	1.75
Group 3	-0.45	0.0	2.75
Group 4	37.53	0.0	1.09

Panel B: Cross-Sectional Regression

	Data	Null	10%	50%	90%
λ_w	-0.083	0.0	-0.065	-0.000	0.064
$t-$stat	-6.310	0.0	-4.050	-0.018	4.011
$adj - R^2$	0.510	0.0	-0.022	0.091	0.400

Panel A of Table VI presents the exposure of real returns on the market portfolio of 38 countries to simulated global temperature. The table reports the estimated temperature beta (Data) and the simulated temperature beta (50%) for each country group. The simulated temperature betas are computed from the fixed-effects model similar to that in Table III, where global temperature is modelled as a first-order autoregressive process. Panel B of Table VI presents the estimated (Data) and simulated market price of temperature risk. The simulated market price of risk is computed from a regression of the average real market return from 38 countries on the simulated temperature beta. The data is annual, and market equity returns are real and expressed in percentage terms.

Table VII

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 VII presents the correlation coefficient between world consumption, world GDP growth and the change in temperature at different horizons. 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. Newey-West Standard errors are presented in parenthesis.

Table VIII

Temperature Impact on Growth Rates

	Dep. Var.: GDP growth	
Coeff.	(1)	(2)
ρ	0.08	0.40
	(0.04)	(0.12)
α_0	-0.18	-0.25
	(0.09)	(0.18)
β_0	-0.24	-0.04
	(0.10)	(0.24)
Observations	7104	47
Countries	147+World	World
R-squared	0.07	0.22

Table VIII presents the results from a regression of GDP growth ($\Delta y_{i,t}$) on standardized temperature (w_t), standardized temperature innovations (ζ_t), and a lag of the dependent variable,

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + \beta_0 \zeta_t + \varepsilon_{i,t}$$

where ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance of country i at time t. The first column presents the results from a regression using a panel of 147 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 growth 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 IX

Temperature, GDP Growth, and Distance to the Equator

	Dep. Var.: GDP growth	
Coeff.	(1)	(2)
ρ	0.08	0.08
	(0.04)	(0.04)
α_0	-0.18	-0.18
	(0.09)	(0.09)
α_1	-0.43	-0.43
	(0.16)	(0.13)
α_2	0.73	
	(0.44)	
α_3		0.27
		(0.25)
α_4		0.57
		(0.27)
α_5		0.17
		(0.17)
Obs.	7057	7057
Countries	147	147
R^2	0.06	0.06

Table IX presents the results from a regression of GDP growth ($\Delta y_{i,t}$) on standardized temperature (w_t), standardized temperature innovations (ζ_t), and a lag of the dependent variable for a panel of 147 countries and a fixed-effects model. Column (1) reports the estimated coefficients from the following fixed-effect model,

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + (\beta_0 + \beta_1 \times \ell_i)\zeta_t + \varepsilon_{i,t}$$

where ℓ_i is country i's distance to the Equator, which is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1, ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance of country i at time t. Column (2) presents the results from the estimated coefficients from the following fixed-effect model

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + \left(\beta_0 + \sum_{j=2}^{4} \beta_j \times \mathbf{I}(\ell_i \in g_j) \right) \zeta_t + \varepsilon_{i,t}$$

where $\mathbf{I}(\cdot)$ is an indicator function, g_j for $j = 1, \ldots, 4$ are intervals which sort countries according to their distance to the Equator, countries with $\ell_i \in g_1$ are those closest to the Equator while countries with $\ell_i \in g_4$ are those furthest from the Equator. The sample covers the period from 1950 to 2007. GDP is real and in per capita terms and 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. Standard errors corrected for autocorrelation and heteroskedasticity are presented in parenthesis.

Table X

Real GDP Growth Exposure to Long-Run World GDP Growth

	Dep. Var.: GDP growth ($\Delta y_{i,t}$)		
Coeff.	$K = 4$	$K = 6$	$K = 8$
γ_0	0.79	0.98	1.09
	(0.17)	(0.23)	(0.26)
γ_1	-0.93	-1.17	-0.89
	(0.44)	(0.57)	(0.62)
Obs.	6104	5882	5660
Countries	147	147	147
R^2	0.06	0.06	0.06

Table X presents the results from a regression of real GDP growth ($\Delta y_{i,t}$) on a measure of long-run world GDP growth (x_t), and long-run world GDP growth interacted with the distance to the Equator, namely,

$$\Delta y_{i,t} = \varsigma_i + (\gamma_0 + \gamma_1 \times d_i)\, x_{t-1} + \varepsilon_{i,t}$$

where d_i is country i's distance to the Equator, which is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1; x_t is long-run world GDP growth, which is computed as the trailing K-period moving average of world GDP growth, $x_t = \sum_{i=1}^{K} \Delta y_t^W$; ς_i is a fixed-effect, and $\varepsilon_{i,t}$ is a random disturbance of country i at time t. Each column presents the regression results for different values of K. The results come from a regression using a panel of 147 countries and a fixed-effects model. 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 XI

Baseline 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	-0.005
Dividends	μ_d	ϕ	π	φ_u	
	0.0015	2.75	4.5	2.0	
Temperature	μ_w	ρ_w	σ_ζ		
	14.0	0.99	0.025		

Table XI reports configuration of investors's 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 independent Gaussian standard innovations.

Table XII

Model Implied Dynamics of Growth Rates and Returns

Moment	Median	5%	95%	Population
$E[\Delta c]$	1.81	0.59	2.99	1.83
$\sigma(\Delta c)]$	2.71	2.18	3.3	2.78
$AC1(\Delta c)$	0.41	0.16	0.62	0.45
$E[w_t]$	14.00	-2.92	6.27	14
$\sigma(w_t)$	0.14	10.19	15.12	0.18
$AC1(w_t)$	0.88	-0.83	0.82	0.92
$corr(\Delta c, \Delta w)$	-0.03	-0.29	0.22	-0.04
$corr(\Delta^5 c, \Delta^5 w)$	-0.10	-0.52	0.38	-0.09
$corr(\Delta^{10} c, \Delta^{10} w)$	-0.13	-0.68	0.56	-0.10
$E[R_m]$	5.70	0.95	10.97	5.98
$\sigma(R_m)$	19.96	16.37	23.9	20.30
$E[R_f]$	1.62	1.13	2.09	1.63
$\sigma(R_f)$	0.78	0.57	1.07	0.85

Table XII reports moments of aggregate consumption (c_t), temperature (w_t), the return on the aggregate stock market (R_t), and the risk-free rate (R_f). Model based statistics, computed from 1,000 simulated samples each with 12×50 monthly aggregated data to annual observations, are presented in the first three columns. The last column presents population statistics based on $12 \times 20,000$ monthly data aggregated to annual observations. Means and volatilities of returns and growth rates are expressed in percentage terms.

Table XIII

Model Implied Impact of Temperature on Growth

Dep. Var.: Consumption Growth (Δc_t)				
Coeff.	Median	5%	95%	Population
ρ	0.36	0.09	0.58	0.43
α_0	-0.28	-1.04	0.40	-0.26
α_1	-0.22	-0.90	0.37	-0.23

Table XIII reports the results from a regression of annual consumption growth (Δc_t) on lagged standardized temperature (w_{t-1}), standardized temperature innovations (ζ_t), and a lag of the dependent variable,

$$\Delta c_t = \varsigma + \rho \Delta c_{t-1} + \alpha_0 w_{t-1} + \alpha_1 \zeta_t + \varepsilon_t$$

The reported statistics are computed from 1,000 simulated samples each with 12×50 monthly aggregated data to annual observations. The last column contains population statistics based on $12 \times 20,000$ monthly data aggregated to annual observations. The growth rate is expressed in percentage terms, and temperature as well as temperature innovations are standardized. Temperature innovations are the residual from regressing temperature on its own lag.

Table XIV

Exposure to Long-Run Risks and Equity Risk Premium

LR Growth Exposure (ϕ_i)	Temperature Beta	Equity Risk Premium	Temp. Risk Premium
0.25	0.02	1.33	-0.03
0.90	-0.07	3.62	0.05
1.90	-0.24	4.50	0.18
2.65	-0.39	5.13	0.27
3.30	-0.48	7.29	0.58
3.80	-0.56	7.94	0.68
4.78	-0.70	10.59	1.06
6.08	-0.89	13.31	1.45
7.25	-1.08	15.10	1.71

Table XIV presents temperature beta, the risk premium on the levered asset, and the compensation from temperature risks for different values of ϕ_i. The dividends in each portfolio has an exposure to long-run growth determined by ϕ_i, namely,

$$\Delta d_{i,t+1} = \mu_{i,d} + \phi_i x_t + \pi_i \sigma \eta_{i,t+1} + \varphi_{i,u} \sigma u_{i,t+1}$$

The risk compensation from temperature risks is calculated as the product of the temperature beta and the market price of temperature risks. The risk premium equals the compensation from short-run, long-run and temperature risks. The risk compensation is annual and expressed in percentage terms.

Table XV

Model Implied Market Price of Temperature Risk

Coeff.	Median	5%	95%	Population
λ_w	-0.11	-0.19	-0.06	-0.13
λ_0	0.04	-0.04	0.14	0.03

Table XV the market price of risk implied by the model using 40 simulated portfolios with varying levels of exposure to aggregate long-run growth. The table presents the results from a cross-sectional regression where the average real return is regressed on the estimated temperature beta for a sample of 40 simulated portfolios ranging from low to high exposure, namely,

$$\bar{R}_i = \lambda_0 + \lambda_w \beta_{i,w} + \epsilon_i.$$

Model based temperature betas as well as the market price of risk are computed from 1,000 simulated samples each with 12×50 monthly aggregated data to annual observations. The last column contains population statistics based on $12 \times 20,000$ monthly data aggregated to annual observations.

Figure I

Temperature Beta and Distance to the Equator

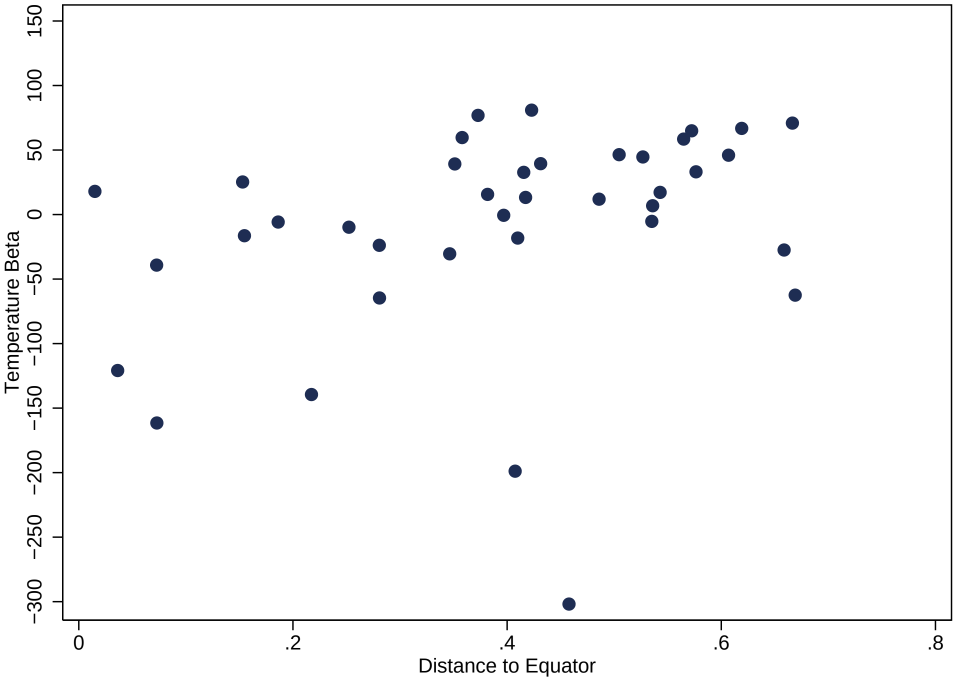

Figure I presents a scatter plot for the estimated temperature beta against the distance to the Equator for a sample of 38 countries. The value of the temperature beta is obtained by regressing the market real return for each country on the change in global temperature. The distance from the equator 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 II.

Figure II

Distance to the Equator and Agriculture share in GDP

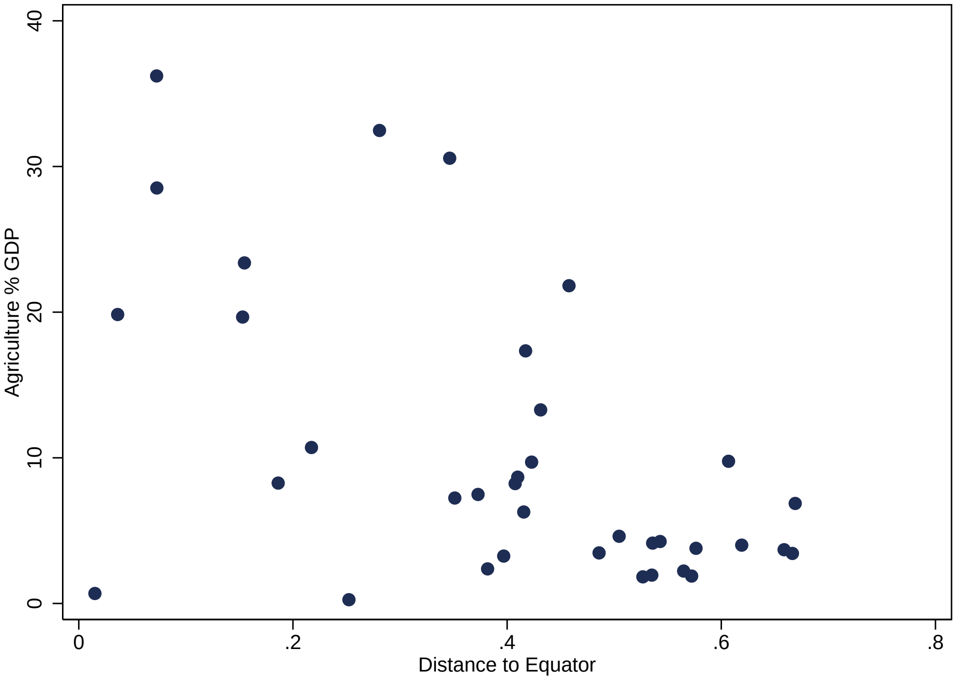

Figure II presents a scatter plot for the share of agriculture in GDP against the distance to the Equator for a sample of 38 countries. The share of agriculture in GDP is computed for the period 1960-2007. The distance from the equator is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1.

Figure III

U.S. Industry Portfolios' Temperature Beta

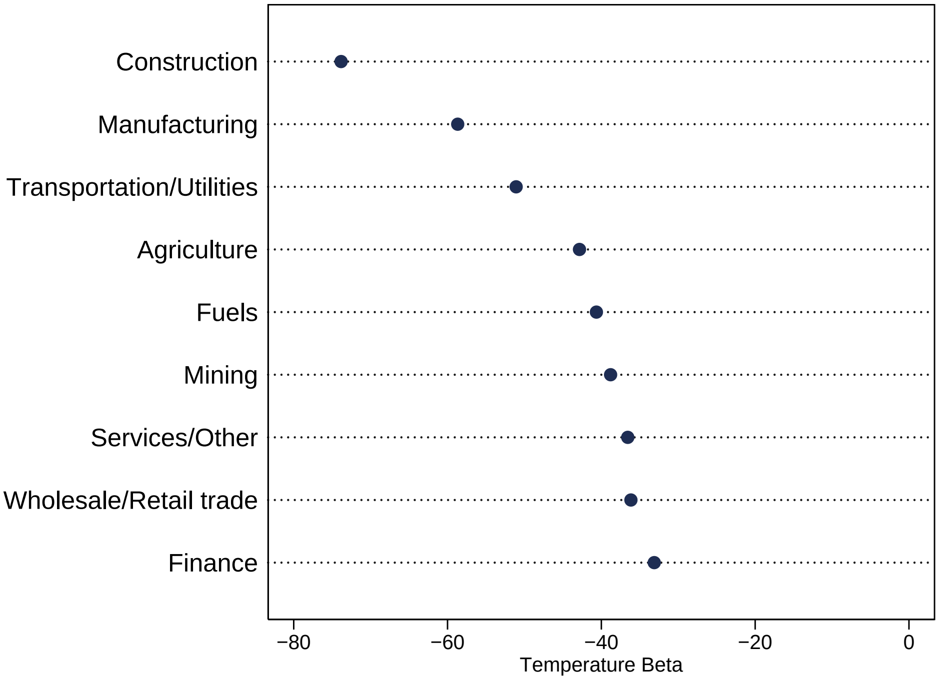

Figure III presents the temperature beta for nine U.S. industry portfolios. The industry groups are constructed using the two digit SIC codes. The temperature beta is obtained by regressing the market real return for each portfolio on the change in global temperature. The data on returns are annual, real, and expressed in percentage terms.

Figure IV

Distance to the Equator and Exposure to Temperature Sensitive Portfolio

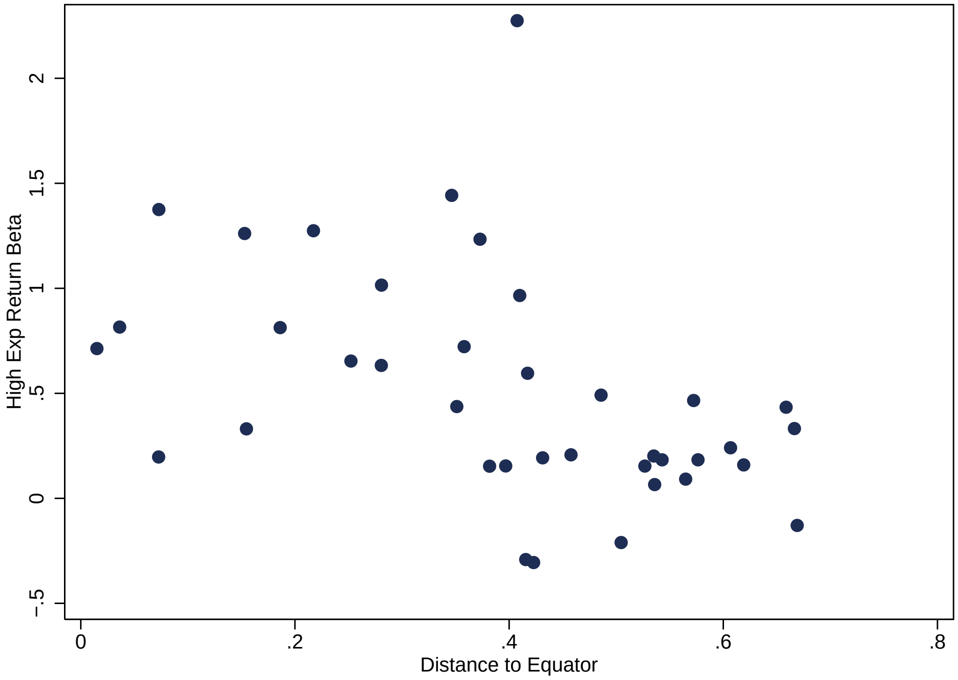

Figure IV presents a scatter plot for the exposure to the return on the temperature sensitive portfolio against the distance to the Equator for 38 countries. The portfolio of temperature sensitive industries is composed of Construction, Manufacturing, Transportation and Utilities, and Agriculture. The exposure of equity market returns to the temperature sensitive portfolio is estimated running a regression of the return on a country portfolio in excess of the risk-free rate ($ER_{i,t}$) on the return on the temperature-sensitive portfolio in excess of the market portfolio (ER_t^H), namely,

$$ER_{i,t} = \beta_{i,0} + \beta_{i,h} ER_t^H + \varepsilon_{i,t}$$

where $\beta_{i,h}$ is country i's exposure to the temperature-sensitive portfolio.

Figure V

Response of Growth to Temperature Shocks

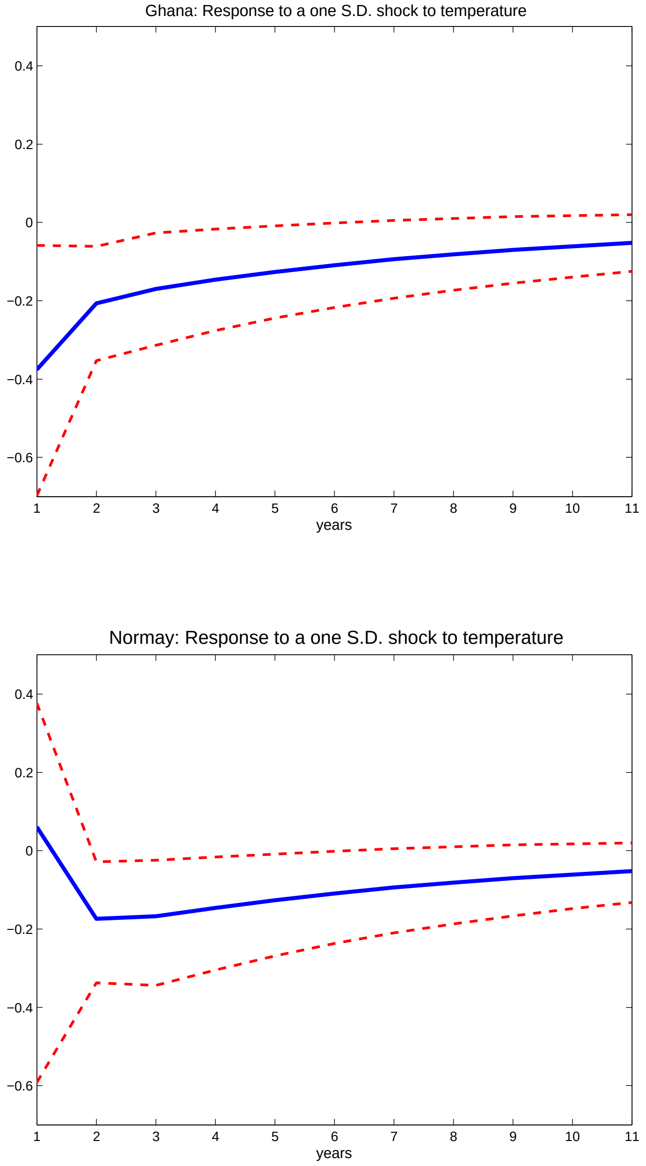

Figure V presents the response of GDP growth to a temperature shock in Ghana ($\ell = 0.07$ close to the Equator) and Norway ($\ell = 0.67$ far from the Equator). The impulse-response functions are computed using the dynamic model of GDP growth presented in Table IX

Figure VI

Temperature Risk at Different Values of the IES

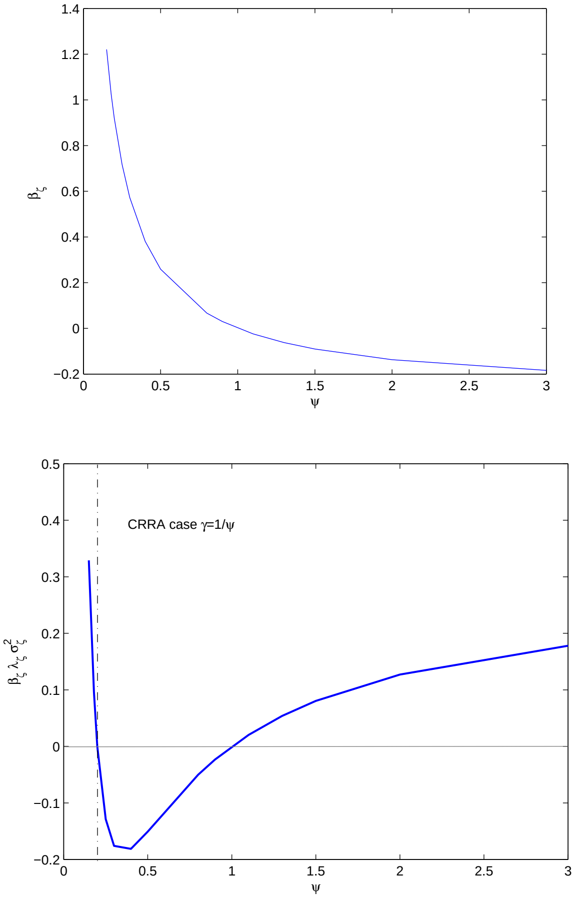

Figure VI plots the temperature beta, and the contribution of temperature innovations to the risk premia at different values of the IES and setting the risk aversion parameter equal to 5. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ). The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

Figure VII

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

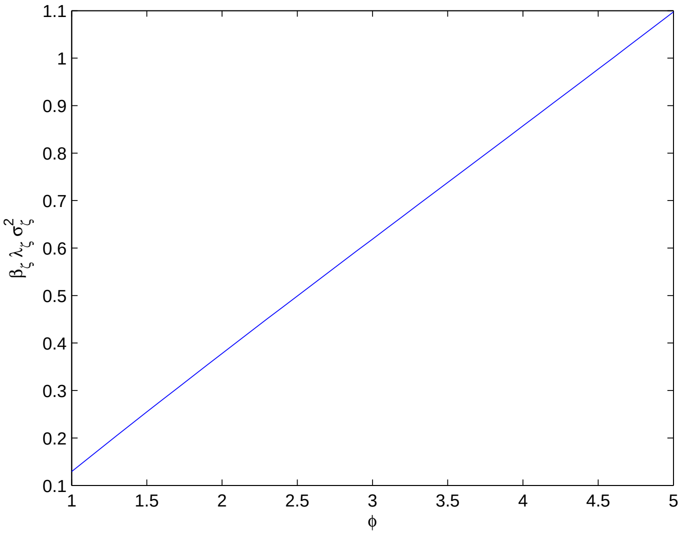

Figure VII the contribution of temperature innovations to the risk premia at different values of dividend's exposure to long-run growth, ϕ. The compensation to temperature innovations, $\beta_{\zeta,m}\lambda_\zeta$, is expressed in annual percentage terms.