Essays in Asset Pricing

by

Marcelo Ochoa

Department of Economics
Duke University

Date: ____________________

Approved:

____
Ravi Bansal, Supervisor

____
Manuel Adelino

____
Francesco Bianchi

____
Craig Burnside

____
Lukas Schmid

Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Economics in the Graduate School of Duke University
2013

Abstract

Essays in Asset Pricing

by

Marcelo Ochoa

Department of Economics
Duke University

Date: ______________________

Approved:

____
Ravi Bansal, Supervisor

____
Manuel Adelino

____
Francesco Bianchi

____
Craig Burnside

____
Lukas Schmid

An abstract of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Economics in the Graduate School of Duke University
2013

Abstract

The three essays in this dissertation explore the role of fluctuations in aggregate volatility and global temperature as sources of systemic risk. The first essay proposes a production-based asset pricing model and provides empirical evidence suggesting that compensation for volatility risk is closely related to an unexplored characteristic of a firm, namely, its reliance on skilled labor. I propose a model in which aggregate growth has time-varying volatility, and linear adjustment costs in labor increase with the skill of a worker. The model predicts that expected returns increase with a firm's reliance on skilled labor, as well as compensation for fluctuations in aggregate uncertainty. Consequently, a rise in aggregate uncertainty predicts an increase in expected returns as well as in cautiousness in hiring and firing. This impact is larger for firms with a high share of skilled workers because their labor is more costly to adjust. I empirically test the implications of the model using occupational estimates to construct a measure of a firm's reliance on skilled labor, and find a positive and statistically significant cross-sectional relation between the reliance on skilled labor and expected returns. Empirical estimates also show that an increase in aggregate uncertainty leads to a rise in expected returns, and this impact is larger for firms which rely heavily on skilled labor; thereby, a firm's exposure to aggregate volatility is positively related to its reliance on skilled labor.

In the second and third essay, co-authored with Ravi Bansal, we explore the impact of global temperature on financial markets and the macroeconomy. In tho

second essay we explore if temperature is an aggregate risk factor that adversely affects economic growth. 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.

The last essay proposes a general equilibrium model that simultaneously models the world economy and global climate to understand the impact of climate change on the economy. We use this model to evaluate the role of temperature in determining asset prices, and to compute utility-based welfare costs as well as dollar costs of insuring against temperature fluctuations. We find that the temperature related utility-costs are about 0.78% of consumption, and the total dollar costs of completely insuring against temperature variation are 2.46% of world GDP. If we allow for temperature-triggered natural disasters to impact growth, insuring against temperature variation raise to 5.47% of world GDP.

Contents

List of Tables

List of Figures

Acknowledgements

I am grateful to my advisor, Ravi Bansal, for his guidance, understanding, and useful discussions, which have been invaluable in my academic growth. I am also grateful to my Dissertation Committee members, Manuel Adelino, Francesco Bianchi, Craig Burnside and Lukas Schmid for their constant help and suggestions. I also want to thank my friends and colleagues, Barry, Domenico, Emily, Mehmet, and Jonas, and the Macro seminar participants at Duke University for many helpful discussions and suggestions.

I am also grateful to my wife, friend and highly regarded colleague, Daniela, for her constant patience and support. Finally, I would like to thank my parents, and my brothers for their encouragement.

1

Labor Heterogeneity, Volatility and Expected Equity Returns

Various studies emphasize the importance of variations in macroeconomic uncertainty to understand fluctuations in asset prices, employment, and investment.[1] More recently, Bansal et al., Bali and Zhou and Campbell et al. provide empirical evidence that compensation for volatility risk is important to understand the cross-sectional variation in equity returns. In spite of the persuasive literature documenting the impact of aggregate macroeconomic uncertainty on asset prices, there is no empirical or theoretical evidence explaining why the compensation for volatility risk is different across stocks. This essay proposes a production-based asset pricing model and provides empirical evidence suggesting that compensation for volatility risk is closely

[1] Most notable papers include Kandel and Stambaugh who explore an equilibrium asset pricing model in which the mean and variance of consumption growth vary through time, Bansal and Yaron who assert that long-run fluctuations in expected growth and long-run fluctuations in consumption volatility are important to explain asset prices, and Bekaert et al. who explore the importance of changes in the conditional variance of dividend growth and time-varying risk aversion in explaining asset markets. Bansal et al., Bollerslev et al., Bollerslev et al., and Bansal et al. present empirical evidence showing that fluctuations in economic uncertainty impact asset valuations. Finally, Bloom et al. and Bloom show that an increase in aggregate uncertainty lowers hiring and investment rates, and consumer durable expenditures.

related to an unexplored characteristic of a firm, namely, its reliance on skilled labor.

In this essay I present a production-based asset pricing model that builds on Bentolila and Bertola, Caballero et al., Cooper and Willis and adds two crucial ingredients. First, I introduce labor heterogeneity. Firms differ in their reliance on skilled labor, and they face linear adjustment costs in labor which are increasing with the skill of the worker. Second, the model has two sources of macroeconomic risk: fluctuations in aggregate productivity and time-varying volatility of productivity growth. The stochastic discount factor to compute the compensation for these risks and asset prices in general comes from the the long-run risks model of Bansal and Yaron. This model provides a laboratory to simultaneously study the impact of aggregate uncertainty fluctuations on a firm's labor demand and its cost of equity, which have been previously explored separately.

The model predicts that expected returns increase with a firm's reliance on skilled labor, and compensation for fluctuations in aggregate uncertainty (i.e, volatility risk) increases with the reliance of a firm on skilled labor. As a consequence, an increase in aggregate uncertainty predicts a rise in expected returns, and this impact is larger for firms that rely heavily on skilled labor relative to firms which rely mainly on unskilled labor. The link between a firm's reliance on skilled labor and its cost of capital results from the following economic mechanism. An increase in aggregate uncertainty slows a firm's labor demand reaction to changes in economic conditions, reducing its ability to smooth cash-flows. This effect will be larger at firms with a high share of skilled workers because their labor is more costly to adjust. Consequently, these firms are more exposed to fluctuations in aggregate uncertainty and investors command a higher return for investing in this type of firms.

The empirical evidence in this essay starts by documenting a positive relationship between a worker's skill and labor adjustment costs using a unique employee-employer matched data set which contains detailed information on several costs the firm incurred filling the most recent vacant position.[2] Motivated by this evidence, I construct an empirical measure of a firm's reliance on skilled labor as an index of labor adjustment costs[3] using the Occupational Employment Statistics (OES) estimates of occupational employment at the three-digit SIC classification along with the U.S. Department of Labor's classification of occupations based on skill-level. The empirical evidence suggests that firms which have a high concentration of skilled labor have higher expected returns on equity relative to those in which a larger share of their labor is unskilled. This conclusion is robust to whether I include controls for known characteristics that explain the cross-section of expected returns, such as the book-to-market equity ratio, market equity, and past performance, as well as predictors of expected returns which might be correlated with a firms's reliance on skilled labor, such us R&D intensity, profitability, operating costs, investment rate, sensitivity of sales to macroeconomic growth, leverage, and labor intensity.

I also provide empirical evidence showing that the risk compensation for a a firm's reliance on skilled labor fluctuates with macroeconomic uncertainty. I find strong empirical evidence suggesting that an increase in aggregate uncertainty leads to a rise in expected returns, and the impact of uncertainty increases with a firm's reliance on skilled labor. Following Bloom, aggregate macroeconomic uncertainty is approximated by implied volatility computed using the VXO index based on S&P 100 index options, and realized volatility computed as the monthly standard deviation of the daily S&P 500 index. Using this two proxies for aggregate uncertainty, the coefficient estimates suggest that a one standard deviation rise in a firm's reliance of skilled labor results in an increase in expected returns of between 2.1% and 3.4%

[2] Parsons and more recently Hamermesh and Pfann survey evidence concluding that these quasi-fixed costs are substantial. They amount to as much as one year of payroll cost for the average worker and seem to increase rapidly with the skill of the worker.

[3] Since labor adjustment costs are not measured or reported on a firm's accounting records, Oi and Rosen also follow this route.

in times of high uncertainty, while in times when aggregate uncertainty is at its historical average the risk compensation for a firm's reliance on skilled labor is less than 1.0%.

Finally, I present evidence suggesting that the risk premium for reliance on skilled labor contains information about systemic risk which is not contained in existing risk factors. First, I show that the reliance on skilled workers premium is not spanned by the market excess return, the size risk factor, and the book-to-market risk factor Fama and French (1996). Then, I explore whether the reliance on skilled workers premium is able to explain the cross-sectional variation in average excess equity returns on 48 industry portfolios which are particularly challenging to explain for both the CAPM and Fama and French three-factor model.[4] When the basic CAPM is augmented with the risk premium for a firm's reliance on skilled labor, the adjusted R^2 increases to 40.2% from -1.2%, and it is twice the size of the R^2 obtained when using the three Fama-French risk factors.

This essay makes the following contributions. First, it links the compensation from fluctuations in aggregate uncertainty to an unexplored characteristic of a firm, namely, the reliance of a firm on skilled workers. Second, it provides a production-based asset pricing model that sheds light on the economic mechanism through which a firm's reliance on skilled labor and its cost of capital relate to each other; consequently, it also provides proposes a link between labor and asset markets. Finally, this paper contributes to the literature exploring empirically and theoretically the interaction between frictions in the labor market and asset prices by linking an observable characteristic of a firm's workforce to differences in labor adjustment costs to explain differences in the compensation for volatility risk.[5]

[4] See, for example, Fama and French.

[5] Danthine and Donaldson proposes a general equilibrium model with labor-induced operating leverage. Matsa, Chen et al., and Schmalz explore the impact that unionization has on capital structure decisions and the cost of equity. Donangelo considers labor mobility, and Merz and

1.1 Conceptual Framework

This section first presents empirical evidence supporting a positive relationship between a worker's skill and the costs of replacing the worker. Then, I incorporate this evidence into an asset pricing model with labor adjustment costs, hence, firms face piecewise linear adjustment costs in labor which are increasing with the skill of a worker. In the model, aggregate productivity growth has a time-varying volatility which captures the idea that uncertainty about future productivity growth fluctuates over time. The model predicts an increasing monotonic relationship between expected equity returns and a firm's reliance on skilled labor. It also suggests that an increase in volatility predicts a rise in expected equity returns, and this effect increases with a firm's reliance on skilled labor. Consequently, these firms are more exposed to fluctuations in aggregate uncertainty and investors command a higher return for investing in firms with a high reliance on skilled labor relative to firms with a high share of unskilled workers because labor adjustment costs are higher for skilled workers.

1.1.1 Worker's Skill and Labor Adjustment Costs

The costs of adjusting labor demand include separation costs (e.g., severance pay), recruiting costs (e.g., advertising, search and agency fees, recruiter time), selection and hiring costs (e.g., interview, orientation, formal and on-the-job training), and costs due to productivity loss (e.g., vacancy cost, learning curve, peer and supervisor disruption) Hinkin and Tracey (2000). Most of these costs are implicit and are neither measured nor reported by firms Hamermesh and Pfann (1996). For example, when new employees join a work crew and senior workers spend time training them disruptions in production arise which translates into a loss of output and productivity,

Yashiv and Bazdrech et al. underscore the importance of labor adjustment costs to explain the risk of equity.

however, these costs are not measured nor reported on the firm's accounting records.

There are few studies which have attempted to quantify the extent of turnover costs, much less the relationship between a worker's skill level and such costs. Some studies concerning single firms or industries have concluded that the costs of adjusting labor large and they amount to as much as one year of payroll cost for the average worker, and these costs increase very rapidly with the skill of the worker (e.g., Oi, Mincer, Merchants and Manufacturers Association (1980) survey, Pfann and Verspagen, Button, Cascio).

This section presents empirical evidence supporting a positive relationship between a worker's skill and the costs of replacing the worker. In the analysis I use the firm-level data from the 1980 Employer Opportunity Pilot Project (EOPP), a unique employee-employer matched data set, which contains information on about 5,200 firms from ten different states in the U.S. and different industries. The EOPP data set contains detailed information on costs the firm incurred filling the most recent vacant position, namely, the time the employer spent recruiting for the position, the number of applicants interviewed for that position, the amount of time employees and supervisory staff spent training the new hire the first month of employment, the level of productivity during the second week of employment, as well as information on the recent hire's education, relevant job experience, and gender. The employer also provides information about maximum hourly wage for the position filled by the last new hire, as well as the productivity level of the last employee in that position.[6]

Table 1.1 presents summary statistics of the relevant variables as well as means conditional on the education of the new employee. From the sample of firms, 69% reported a newly hired. On average, these firms spent 18 days recruiting, interviewed about 5 candidates, during the employee's first month of tenure superiors and em-

[6] The information is about the last position filed between January of 1978 and October of 1979. The Data Appendix contains the specific questions for gathering labor adjustment costs.

ployees spent 37 hours away from normal work routines orienting and training her, and during the second week of employment the employee was on average 15% less productive than the person she replaced on that occupation.

To explore how these costs vary with the skill and expertise the employer requires for the vacant position, I estimate the following model,

$$cost_i = \alpha + \beta\ skill_i + \mathbf{x}_i'\delta + u_i \tag{1.1}$$

where $cost_i$ is a component of labor adjustment costs for position i, and $skill$ corresponds to a measure of skill, and u_i is the error term. I use two alternative measures of skill, the education of the newly hired and the top hourly wage for that position. It is reasonable to assume that the education of the newly hired and the max hourly wage for the position are both positively related to the level of skill and expertise the employer needs to fill the vacant position. The vector $\mathbf{x}$ of control variables contains age, gender and relevant experience of the recent new hire, as well as the size of the firm computed as the number of full-time and part-time employees and dummy variables to control fixed industry characteristics at the 2-digit SIC level.

First, I explore the relationship between the education of the newly hired and labor adjustment costs. Table 1.2 presents the estimated coefficients from equation (1.1) where each column considers as dependent variable one component of the following costs of filling a vacant position: the number of days an employer spent filling the position, the number of applicants interviewed for the position, the hours spent by employees and supervisors training the last new hire, and the last new hire productivity gap defined as the productivity of the last employee in the position relative to the productivity of the new employee during the second week of employment. Education is a dummy variable which is equal to one if the new employee has a high-school diploma or more years of education. The estimated coefficient on education of the recent new hire is positive and statistically different from zero across all components of labor adjustment costs. For example, if the newly hired has finished high-school or more the expected number of days recruiting increases by about 7, employers expect to interview two more persons, provide 6 hours more training, and the new hire productivity to perform a job will be about 4% lower.

Table 1.3 presents the estimated coefficients of a regression of labor adjustment costs on the (log) max wage per hour for that position. Again, the regressions include controls for age, gender and relevant experience of the recent new hire, as well as firm size and dummy variables for industry at the 2-digit SIC level. In line with the previous evidence, results show that the time recruiting and the number of people interviewed for that position, the hours of training of the new hire, as well as the productivity gap increase with the level of the vacant position's top wage. The estimated coefficients imply that the time recruiting increases by 15 days when the position's top wage doubles. Similarly, the number of people interviewed increases by two, the hours of training go up by 18, and the productivity gap is 4.8 percentage points higher.

From the results presented in Tables 1.3 and 1.2 we can conclude that the level of education of the newly hired and the top hourly wage for the vacant position are positively related to costs of replacing a worker such us time recruiting, training, and loss productivity. Consequently, the cost of replacing a worker increases with the skill of the worker which is consistent with studies concerning single firms or specific industries, and Dolfin who finds that higher costs are associated with lower turnover rates.

1.1.2 Asset Pricing Model with Adjustment Costs

Dynamic Problem of the Firm

Consider an economy populated by competitive firms which produce a good using labor as the only input. Firm i's output at time t is produced by the following

Cobb-Douglas production function,

$$y_{i,t} = A_t \left(h_{i,t} n^e_{i,t}\right)^{\alpha} \tag{1.2}$$

where A_t is stochastic aggregate productivity, $h_{i,t}$ the input of hours per worker, $n^e_{i,t}$ represents the stock of workers measured in efficiency units. As in Kydland, a firm relies on two type of workers, high-skilled n^1 and low-skilled n^2 workers. Let $\lambda > 1$ represent the relative productivity of high-skilled workers, then a firm's stock of workers measured in efficiency units is given by,

$$n^e_{i,t} = \lambda n^1_{i,t} + n^2_{i,t} \tag{1.3}$$

Firms are heterogeneous with respect to the mix of high-skilled and low-skilled workers they use in their production process. In particular, each firm uses a fraction

$$\omega_i = \frac{n^1_{i,t}}{n^1_{i,t} + n^2_{i,t}}$$

of high-skilled workers.

Adjustments to labor demand give rise to adjustment costs. In particular, a firm adjusting labor of type j must incur in a cost χ^j for every job it creates or destroys,

$$C^j(n^j_{i,t}, n^j_{i,t-1}) = \chi^j \| n^j_t - n^j_{t-1} \| \quad \text{for } j = 1, 2 \tag{1.4}$$

The costs χ^j corresponds to the cost of separation, time recruiting, time training, and costs due to productivity loss for every job created or destroyed.[7] Consistent with the empirical evidence presented in Section 1.1.1, the cost of labor adjustment is higher for high-skilled workers than for low-skilled workers, that is, $\chi^1 > \chi^2$.

A firm's dividends consist of output less the total compensation to workers and costs of labor adjustment,

$$d_{i,t} = y_{i,t} - w(h_{i,t})(\lambda n^1_{i,t} + n^2_{i,t}) - \sum_j C^j(n^j_{i,t}, n^j_{i,t-1}) \tag{1.5}$$

[7] Using a more general cost function which distinguishes between costs of destroying and creating a job does not have an impact on the main results.

where the total compensation to high-skilled and low-skilled workers is given by $w(h_{i,t})\lambda n^1_{i,t}$ and $w(h_{i,t})n^2_{i,t}$, respectively. As in Caballero and Engel and Cooper and Willis the compensation function $w(h)$ is given by,

$$w(h) = w_0 + w_1 h^{\zeta} \tag{1.6}$$

where $\zeta - 1$ is the marginal wage elasticity to hours. In the case when $\zeta = 1$ Cooper and Willis note that the firm will optimally choose to adjust hours in face of productivity shocks in order to avoid the adjustment costs that arise from changing the number of workers. To obtain a joint response of hours and employment it must be that $\zeta \neq 1$.

Aggregate productivity growth is stochastic and follows an auto-regressive process with stochastic volatility,

$$a_t = \mu + \rho a_{t-1} + \sigma_{t-1}\epsilon_t \tag{1.7}$$

where ϵ_{t+1} is an independent identically distributed standard normal process. On the other hand, I assume that volatility σ_t follows a persistent Markov chain capturing the idea that firms uncertainty about aggregate growth fluctuates over time.

The firm's recursive problem is to choose employment and hours to maximize the market value of the firm by solving,

$$\nu_i(\mathbf{s}_{i,t}) = \max_{n_{i,t},h_{i,t}} d_{i,t} + \mathbb{E}_t\left(M_{t,t+1}\nu_i(\mathbf{s}_{i,t+1})\right) \tag{1.8}$$

where the state of the economy is given by $\mathbf{s}_{i,t} = (n_{i,t-1}, A_t, a_t, \sigma_t)$, $\nu_i(\mathbf{s}_{i,t})$ is the cum-dividend market value of firm i at time t, and $M_{t,t+1}$ is the stochastic discount factor. Notice that when a firm chooses employment $n_{i,t}$, the value of ω_i determines the number of skilled and unskilled workers the firm utilizes, namely, $n^1_{i,t} = \omega_i n_{i,t}$ and $n^2_{i,t} = (1 - \omega_i)n_{i,t}$.

Firms take as given the stochastic discount factor which is derived from the problem of a representative investor with Epstein and Zin and Weil type of recursive preferences. As shown in Bansal and Yaron, this preference structure implies the following stochastic discount factor,

$$M_{t,t+1} = \beta^{\frac{1-\gamma}{1-1/\psi}} \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma} \left(\frac{Z_{t+1}+1}{Z_t}\right)^{\frac{1/\psi-\gamma}{1-1/\psi}}$$

where $0 < \beta < 1$ is the subjective discount factor, γ is the coefficient of risk aversion, and ψ is the intertemporal elasticity of substitution (IES), $\frac{C_{t+1}}{C_t}$ is the representative investor's consumption growth, and Z_t is the wealth-consumption ratio. Notice that this type of preferences allow a distinction between the coefficient of risk aversion γ and the IES ψ, when $\gamma = \frac{1}{\psi}$ the stochastic discount factor collapses to the case in which the representative investor's preferences are CRRA. Finally, I assume consumption growth is positively related to technology growth,

$$\Delta c_t = \mu(1-\phi) + \phi a_{t-1} + \nu_t \tag{1.9}$$

where ν_t is an independent identically distributed standard normal process with variance σ_ν.

Productivity growth a_t and stochastic volatility σ_t are the driving force behind the fluctuations of both aggregate productivity A_t and consumption C_t, and consequently are the sources of systemic risk. The stochastic discount factor pertinent for the problem at hand corresponds to the case when the investor has a preference for early resolution of uncertainty, or more specifically to the case where the relative risk aversion is greater than the inverse of the IES $\gamma > 1/\psi$. As shown in Bansal and Yaron, under this assumption the investor dislikes negative shocks to expected consumption growth and unexpected increases in aggregate volatility. Consequently, shocks to volatility will carry a separate risk compensation.

The return on equity is defined as,

$$R_{i,t+1} = \frac{\nu_i(\mathbf{s}_{i,t+1})}{\nu_i(\mathbf{s}_{i,t}) - d_{i,t}} \tag{1.10}$$

From the Bellman equation (1.11) characterizing the recursive problem of the firm, it follows directly that $R_{i,t+1}$ satisfies the standard asset pricing restriction condition $1 = \mathbb{E}_t \left(M_{t,t+1} R_{c,t+1} \right)$. The risk-free rate and the market price of risk are given by,

$$R_t^f = 1/\mathbb{E}_t \left(M_{t,t+1} \right)$$

Optimal Employment Choice

The firm's hiring and firing decisions, the return on equity, the value of the firm, all are function of the state variables of the economy. Because of the complexity of the model I solve the model using numerical methods for a set of parameters specified in Table 1.4. In this section I present the properties of the policy functions which will be useful to understand the exposure of firms to aggregate risk and I detail the numerical solution method to compute these functions in Appendix A.

Taking advantage of the homogeneity of the production function and the firm's constraints, I normalize all variables by aggregate productivity. Let $\tilde{x}_t = \frac{x_t}{A_t^{1/(1-\alpha)}}$ for any variable x, then the stationary representation of the firm's problem is given by,

$$\tilde{\nu}(\tilde{n}_{t-1}, a_t, \sigma_t) = \max_{\tilde{n}_{i,t}, h_{i,t}} \tilde{d}_{i,t} + \mathbb{E}_t \left(M_{t,t+1} \left(\frac{A_{t+1}}{A_t} \right)^{1/(1-\alpha)} \tilde{\nu}(n_t, a_{t+1}, \sigma_{t+1}) \right) \tag{1.11}$$

In the presence of piecewise linear costs of adjusting labor the optimal decision of the firm consists of two aspects: at what points action should be taken, and what the action should be Dixit (1993); Stokey (2009). Specifically, the firm chooses an interval (b^*, B^*) such that when the labor-productivity ratio $\tilde{n}_{i,t}$ is inside this interval the firm chooses inaction, that is the stock of workers remains unchanged $n_t = n_{t-1}$, whereas when the labor-productivity ratio leaves the inaction region the firm chooses to hire or fire workers. Panel (a) of Figure 1.1 displays the optimal choice of labor-aggregate productivity ratio $\tilde{n}_{i,t}$ along with the optimal inaction region $(b^*(x_t, \sigma_t), B^*(x_t, \sigma_t))$. While the labor-productivity ratio $\tilde{n}_{i,t-1}$ remains inside the inaction region the firm does nothing. If aggregate productivity increases sufficiently such that the labor-productivity ratio falls below b^*, the firm immediately hires workers so that the labor-productivity ratio is equal to the lower barrier b^*. In contrast, if productivity falls sufficiently such that the labor-productivity ratio increases above B^*, the firm will fire workers such that the labor-productivity ratio achieves the upper barrier point $B^*(x_t, \sigma_t)$.

Panel (b) of Figure 1.1 displays the effects of variations in aggregate volatility on the optimal inaction regions. An increase in aggregate uncertainty σ_t enlarges the range of inaction because the possibility that a firm may find hiring or firing unwarranted increases. In particular, b^* decreases sharply as uncertainty increases but has very little impact on B^*. Consequently, the firm will wait until aggregate economic conditions are sufficiently good to start hiring when uncertainty is high compared to times when uncertainty is low. In this environment in which aggregate uncertainty fluctuates, the presence of piecewise linear costs implies that inactivity in employment adjustment increases as economic conditions become more uncertain.[8]

Asset Pricing Implications

I now turn to investigate the implications of the model concerning the cross-section of equity returns. Recall that the cross-sectional variation in the model arises due to differences in the extent to which firms rely on high-skilled workers (ω_i). Panel (a) of Figure 1.3 displays the average equity return on a firm with a share of skilled workers ω in excess of the return on the firm with the lowest ω, $\mathbb{E}\left(R_\omega - R_{\underline{\omega}}\right)$, along different values of ω. As firms rely more on high-skilled workers, that is, as ω increases, the expected excess return on equity increases. Therefore, investors will require a higher compensation for investing in firms in which a larger share of their workers is skilled

[8] This result is consistent with the standard comparative static result presented in Stokey where the optimal thresholds are computed comparing permanent differences in uncertainty.

labor. Panel (b) of the same figure displays the change in expected equity returns in excess of the return on the firm with the lowest ω when uncertainty increases one standard deviation, $\partial \mathbb{E}\left(R_{\omega} - R_{\underline{\omega}}|\sigma_t\right)/\partial\sigma$. A rise in volatility predicts an increase in the risk compensation for the reliance on skilled workers suggesting that the exposure of firms to volatility fluctuations increases with their reliance on skilled labor.

To gauge the contribution of volatility fluctuations in explaining the cross-section of equity returns, I solve the problem's dynamic problem assuming that aggregate growth volatility is constant. Figure 1.4 displays the expected equity return on a firm with a share of skilled workers ω in excess of the return on the firm with the lowest ω. The line with circular markers comes from the baseline model assuming time-varying aggregate volatility while the line with cross markers corresponds to the case in which aggregate volatility is constant. The simulation results suggest that the compensation for volatility risk increases with the reliance on skilled workers. Moreover, compensation for volatility risk is quantitatively more important for firms with a high share of skilled workers, consequently, volatility risk compensation is quantitatively more important than compensation for growth risk in explaining the risk premia for firms with a high share of skilled labor.

The model suggests that the spread in expected returns is explained mainly by risks emanating from changes in aggregate uncertainty. To better understand the asset pricing implications of the model it is helpful to inspect the optimal inaction regions for a firm with high share of unskilled workers (low-ω) and one with a high share of skilled workers (high-ω). Figure 1.5 displays the effects on the optimal inaction region of increasing levels of aggregate uncertainty level. First note that an increase in aggregate uncertainty has a different impact on the optimal inaction regions across firms, evidently an increase in aggregate uncertainty widens the inaction region of a high ω firm more markedly than that of a low ω firm because the former faces lower costs of adjusting labor. Consequently, a firm with a high share of skilled workers (high ω firm) will adjust labor less frequently and only when economic conditions are much brighter or in face of gloomier economic conditions in comparison to a firm that relies on unskilled workers (low-ω firm). Consequently, an increase in aggregate uncertainty increases cautiousness relatively more in firms with a high share of skilled workers and are expected to spend a longer time inside the inaction region which translates into a longer period in which the firm's cash-flows positively correlate with economic conditions, thereby are more risky.

1.2 Empirical Evidence

This section empirically tests the implications of the model. Specifically, I explore the relationship between a firm's reliance on occupations with high levels of skill and its expected equity returns. I present evidence based on regressions of stocks at the firm and industry level, and I also present evidence based on sorts of returns as suggested in Fama and French. I find a positive and statistically significant cross-sectional relation between the reliance on skilled labor and equity returns. Consistent with the model, the spread of average returns between firms with high and low share of skilled workers increases with aggregate uncertainty. These results are robust even after controlling for predictors of average equity returns known in the literature which are unrelated to the costs of adjusting labor but that are possibly correlated with the concentration of skilled labor in a firm. Furthermore, I present evidence that the reliance on skilled labor premium is not spanned by known risk factors and contains additional information about systemic risk.

1.2.1 Reliance on Skilled Labor as an Index of Labor Adjustment Costs

Most of labor adjustment costs are implicit and are not measured or reported on a firm's accounting records, however, the evidence presented in Section 1.1.1 suggests that it is possible to use increasing skill-levels as a proxy for increasing adjustment costs. This approach was also taken for example in Oi and Rosen, and I also follow this route.

To proxy the distribution of skilled workers I propose the reliance on skilled labor index defined as,

$$\text{LSKILL}_j = \sum_{i=1}^{O} \left(\frac{L_{ij}}{L_j} z_i \right) \tag{1.12}$$

where L_{ij} is the number of employees in industry j at occupation i, L_j is the total number of employees in industry j, and z_i is the U.S. Department of Labor's classification of occupations based on skill-level, that is, how much education, related work experience and how much training an employee needs to perform the work at a competent level. This program classifies occupations into five "job zones," ranging from job zone 1, $z_i = 1$, which includes occupations that need little or no skills (e.g., counter and rental clerks, construction laborers, and waiters/waitresses) to job zone 5, $z_i = 5$, which consists of occupations that need extensive skill levels (e.g., lawyers, aerospace engineers, surgeons, treasurers, and controllers). Consequently, the workers' skill index (1.12) attains values between 1 and 5. Low values of the index imply that the industry's majority of occupations need little or no skill to perform their job, while high values of the index imply that a large share of the industry's occupations are filled with employees who need extensive skill levels to adequately perform their job.

I compute this measure for each year and industry for the period 1988–2010. Following Hou and Robinson I define the industry membership using the three-digit SIC code. To compute this measure I use the Occupational Employment Statistics (OES) estimates of occupational employment at the three-digit SIC classification along with the U.S. Department of Labor's O*NET program classification of occupations based on skil. The appendix contains a more detailed description of the data sources.

Table 1.5 presents summary statistics on the cross-sectional and time-series variation in the reliance on skilled labor index for selected industries with the highest and lowest values of the index for the period 1988–2010. The reliance on skilled labor index shows important cross-sectional variation across industries. As an example, the industries with the highest value of the index, engineering and architectural services, colleges and universities, legal services, while the bottom three industries are maintenance services to buildings, automobile parking, eating and drinking places. On the other hand, the reliance on skilled labor index does not show much time-series variation, which suggests that most of the variation in the workers' skill index comes from cross-sectional differences.[9] The list of industries in Table 1.5 also suggests that defining a firm's industry membership by its three-digit SIC groups together firms that are in similar lines of business as argued in the work of Hou and Robinson. The sample contains information for 312 industries.

1.2.2 Data sources for financial variables

For the empirical exercises, I use monthly stock returns from the Center for Research in Security Prices (CRSP), and accounting information from the CRSP/COMPUSAT Merged Annual Industrial Files. The sample of firms includes all NYSE-, AMEX, and NASDAQ-listed securities which are identified by CRSP as ordinary common shares (with share codes 10 and 11) for the period between January 1987 and June 2011. Following Fama and French, the sample excludes banks and financial firms (Standard Industrial Classification codes between 6000 and 6999), and firms with negative book equity in $t-1$.

I use a firm's industry membership as defined by the three-digit SIC code to

[9] Alternatively, the level of skill of an occupation z can also be approximated by the hourly wage of an occupation. In fact, the job zones defined by the Department of Labor are closely correlated with the hourly wage on each occupation. In particular, the correlation between the reliance on skilled labor index (1.12) and the average hourly wage across industries is above 80% between 1999 and 2010. However, I will use the index computed using the job zones because the OES program started collecting information on wages only after 1999, but it collects data on employment by occupation and industry since 1988.

match the firm with the corresponding reliance on skilled labor index (LSKILL). The empirical exercises also use information about a firm's (log) book-to-market equity (lnBM), (log) market equity (lnME), R&D intensity (R&D) measured as R&D expenditures as a share of the firm's market equity, operating leverage (OL) measured as the ratio of operating costs to total assets value, profitability (E/A+) measured as positive earnings before interest divided by total assets, assets growth (ASSETG) defined as the annual growth in asset value, sales beta (SALESB) measured as the slope coefficient from a regression of a firm's annual growth in sales on annual GDP growth using quarterly data, labor intensity (LABINT) defined as the ratio of number of employees to total assets value, and total leverage (LEV) measured as the ratio of book liabilities (total assets minus book equity) to total market value of firm (market equity plus total assets minus book equity).

I match CRSP monthly stock return data from July of year t to June of $t+1$ with accounting information from the fiscal year ending in year $t-1$ and with the reliance on skilled labor LSKILL computed in May of year t. The main sample contains 793,948 observations for 10,890 firms across 312 industries. Table 1.6 presents the summary statistics of the variables used in the empirical exercises.

1.2.3 Reliance on Skilled Labor and Expected Equity Returns

This section starts by exploring the spread in realized average returns of five portfolios sorted on the reliance on skilled labor index (LSKILL). In the spirit of Fama and French, in June of each year I sort firms according to their reliance on skilled labor into five portfolios, and I compute monthly equally- and value-weighted returns on these portfolios from July through June of the following year. For each portfolio I compute monthly returns in excess of the risk free rate starting on July of 1988 to the end of June of 2011.

Table 1.7 presents monthly excess returns on the five portfolios sorted on the reliance on skilled labor along with the tests for monotonicity proposed in Patton and Timmermann and Wolak. The average excess returns are increasing in the reliance on skilled labor index, and the difference in returns between the top and bottom quintiles for both the equally-weighted and value-weighted portfolios is positive, and statistically significant for the equally-weighted portfolio. In particular, the spread is 0.497% (6.13% in annual terms) and 0.309% (3.77% in annual terms) for the equally-weighted and value-weighted portfolios, respectively. The Patton and Timmermann monotonicity relation tests, MR–test and MR^{all}–test, confirm that excess returns are monotonically increasing across both equally-weighted and value-weighted portfolios. The MR-test and MR^{all}–test both reject the hypothesis that the excess returns for equally-weighted and value-weighted portfolios are identical or weakly declining in favor of a monotonically increasing pattern. Similarly, the Wolak test cannot reject the null of an increasing relation between excess returns and the reliance on skilled labor. These set of tests are consistent with the presence of a monotonically increasing relationship between excess returns and the reliance on skilled labor for both equally-weighted and value-weighted portfolios.

Firms in the sample differ from each other not only in their reliance on skilled workers but also in other characteristics which might be correlated with the reliance on skilled labor index and average equity returns, in particular, firm's characteristics known to explain patterns in average returns. Table 1.8 Columns (1)–(4) present the estimated coefficients from a regression of firm-level monthly stock returns on the workers' preparation index controlling for known predictors of average returns, namely,

$$r_{ij,t+1} = \alpha + \beta_1 \text{LSKILL}_{j,t} + \mathbf{x}'_{ij,t}\gamma + u_{ij,t+1} \tag{1.13}$$

where r_{ij} is the monthly stock return of firm i from industry j in excess of the risk-free rate, $\text{LSKILL}_{j,t}$ is the reliance on skilled labor index at industry j, and $\mathbf{x}_{ij,t}$ is a vector of firm characteristics which include the (log) book-to-market equity ratio lnBM, (log) market equity lnME, the past month performance $r_{0,1}$, and dummy variables to control for industry fixed-effects at the 1-digit SIC level and year fixed-effects. As explained above, industry membership j is defined by the firm's three-digit SIC level and it is used to match each firm with its corresponding reliance on skilled labor index (LSKILL). The table reports in parenthesis standard errors that are corrected for cross-sectional correlation at the three-digit SIC industry level.

In all specifications the coefficient on the LSKILL is positive and statistically significant. This result suggests that firms which have a high concentration of skilled labor have higher expected returns than those in which a larger share of their employees require little or no skills. The results in columns (2) and (3) show that the LSKILL has a significant predicting power even after controlling for book-to-market and market capitalization. Also, in all specifications both the book-to-market and market capitalization are statistically significant and have the expected signs.

The results presented so far can face two potential problems noted in Fama and French. First, the results can be driven by small market capitalization because they account for a large fraction of the stocks and they tend to have more extreme returns. Second, the regression coefficients can be influenced by extreme values observed on individual stocks. To deal with these concerns, I present two additional estimates to check the robustness of the results. To asses if the predictive power of the workers' skill index is not driven by small market capitalization firms I compute weighted estimates in which firms are weighted according to their market capitalization, and to minimize the impact of extreme returns I construct industry portfolios defining the industry membership by its three-digit SIC code. Columns (5) and (6) of Table 1.8 present the results from these robustness checks. Either using industry portfolios, or a capitalization weighted least-squares estimator, the coefficient on LSKILL is positive and statistically significant.

The evidence based on portfolio sorts and the cross-sectional regressions confirms the first implication of the model, there is a strong monotonic increasing pattern between returns and the reliance on skilled labor. This conclusion is robust to whether we include controls for known characteristics that explain the cross-section of expected returns such us book-to-market equity ratio and market equity, and to alternative empirical strategies.

It is still possible that the reliance on skilled labor LSKILL is capturing the impact of omitted predictors of average equity returns already known in the literature which are unrelated to the costs of adjusting labor. To address this concern, Table 1.9 presents the estimated coefficients of model (1.15) extending the baseline specification to include additional control variables suspected to be correlated with the reliance of a firm on skilled labor and average equity returns.

Columns (1)–(4) of Table 1.9 extend the baseline specification to include controls for R&D intensity (R&D), operating leverage (OL), profitability (E/A+), and assets growth (ASSETG). Chan et al., Li and Lin find a positive relation between R&D intensity and expected stock returns. Lev (1974), and more recently Novy-Marx show that firms with higher levels of operating leverage have higher average equity returns. Similarly, Haugen and Baker and Cohen et al. find that firms with higher levels of profitability have higher expected returns, and Fairfield et al., Titman et al., and Bazdrech et al. find that firms that invest more have lower equity returns. After controlling for these variables, the estimated coefficient on LSKILL remains positive and statistically different from zero. Moreover, the coefficients on the additional control variables have the expected sign and are statistically significant which suggests that these variables capture the cross-sectional variation in average equity returns, but the reliance on skilled labor LSKILL has additional information about the risk of equity.

Columns (5)–(7) of Table 1.9 include controls for the cyclicality of revenues

(SALESB), labor intensity (LABINT), and leverage (LEV). These additional variables rule out the possibility that the reliance on skilled labor LSKILL is capturing differences in the response of firms to the cycle as well as differences in labor intensity and leverage.[10] Regardless of the additional control variables, the workers' skill index remains a highly significant predictor of expected returns. Moreover, it is also important to notice that the estimated parameter across all specifications not only remains statistically significant but its magnitude remains stable. The implied increase in annual expected equity returns due to a one standard deviate increase in the workers' skill index varies between 1.1% and 1.9%.

The evidence presented in this section points towards one conclusion, firms which have a high concentration of employment that requires high levels of skill have higher expected returns than those in which a larger share of their employees require little or no skills. The coefficient estimates suggest that a one standard deviation increase in the workers' preparation index increases annual equity returns by about 1.6%.

1.2.4 Aggregate Volatility and Reliance on Skilled Labor

The theoretical model has a second implication which is useful to identify the impact of labor adjustment costs on the cost of equity: when economic conditions are more uncertain, investors increase the required rate of return for firms which rely more on skilled labor because these firms face higher costs of adjusting labor.

To quantify the impact of aggregate volatility on the premium implied by the reliance on skilled labor index, I estimate equation (1.15) and I allow the coefficient on LSKILL to vary with aggregate uncertainty, that is,

$$r_{ij,t+1} = \alpha + (\beta_1 + \beta_2\sigma_t) \times \text{LSKILL}_{j,t} + \mathbf{x}'_{ij,t}\gamma + \beta_3\sigma_t + u_{ij,t+1} \qquad (1.14)$$

[10] Pratt finds that firms that are labor intensive will have lower leverage because they face higher costs of distress. In default, a proportion of the firm's employees lose their jobs, and the human capital investment embodied in these employees is lost.

where σ is a measure of aggregate volatility, r_{ij} is the monthly stock return of firm i from industry j in excess of the risk-free rate, $\text{LSKILL}_{j,t}$ is the reliance on skilled labor index at industry j, and $\mathbf{x}_{ij,t}$ is a vector which includes the set of firm's characteristics used in the previous section, and dummy variables to control for industry fixed-effects at the 1-digit SIC level and year fixed-effects. I consider two proxies of aggregate volatility, the implied volatility computed using the VXO index based on S&P 100 index options, and the realized volatility computed as the monthly standard deviation of the daily S&P 500 index. As shown in Bloom and Bloom et al., these two measures of aggregate stock market volatility are strongly correlated with other measures of productivity and demand uncertainty such as the cross-sectional standard deviation of firms' pretax profit growth, the standard deviation of Total Factor Productivity growth within the manufacturing sector, and the dispersion over GDP growth predictions of professional forecasters. Therefore, the VXO index and the S&P 500 realized volatility are good proxies for aggregate uncertainty.

Table 1.10 presents the estimated coefficients of equation (1.14). To ease interpretation, I standardize the two measures of aggregate uncertainty, the VXO index and the S&P 500 realized volatility. For both measures of aggregate uncertainty, the coefficient on the reliance on skilled labor index LSKILL is positive but only statistically significant in one specification. However, the coefficient on the interaction between aggregate uncertainty and the reliance on skilled labor index is positive and statistically different from zero for all specifications. The estimated coefficients imply that the workers' skill premium is higher in times of high uncertainty than in times of low uncertainty. For example, if the VXO index increases one standard deviation above its historical mean, a one standard deviation increase in the workers' skill index results in an annual premium of about 5.5%, while in times where uncertainty is at its average level the premium is about 1.2%. Similarly, if the realized volatility of the S&P 500 increases by one standard deviation above its historical mean, the premium arising from the workers' preparation index is about 2.9%, more than twice in normal times when it is about 1.2%.

Alternatively, I explore the impact of aggregate volatility on the time-series premium generated by the reliance on skilled labor. I use two measures of this risk premium, the spread in returns between the top and bottom quintiles of portfolios sorted on the reliance on skilled labor index, and the risk premium generated by the reliance on skilled labor index from Fama and MacBeth estimates.[11] Table 1.11 reports the estimated coefficients of a time-series regression of the risk premium generated by the reliance on skilled labor on aggregate uncertainty, namely,

$$rp_{t+1} = \alpha + \beta_1 \sigma_t + \mathbf{x}_t' \beta + u_{t+1} \tag{1.16}$$

where $\mathbf{x}_t$ includes the 3-month Treasury bill rate (y_t^{3m}), and the premium between the 10-year Treasury bond and a 3-month Treasury bill ($y_t^{10y} - y_t^{3m}$) to control for other variables linked to the business cycle. The coefficient accompanying the two measures of aggregate uncertainty, the VOX index and S&P 500 realized volatility, is positive and statistically different from zero. Both measures of aggregate uncertainty are strong predictors of the premium generated by the workers' skill index even after controlling for other variables related to the business cycle. Moreover, aggregate uncertainty is the only statically relevant predictor of the workers' skill premium.

All in all, the evidence based on cross-sectional regressions and portfolio sorts conclude that when economic conditions are more uncertain, investors increase the required rate of return for firms which rely relatively more on employees with high-

[11] Following Fama and MacBeth, I estimate the following cross-sectional regression for each month in the sample,

$$R_{ij,t+1} = \alpha_t + \beta_{t,1} \text{LSKILL}_{j,t} + \mathbf{x}_{ij,t}' \gamma_t + u_{ij,t+1} \text{ for } t = 1, .., T \tag{1.15}$$

and obtain a time-series of the risk premium implied by the reliance on skilled labor index $\{\beta_{t,1}\}_{t=1}^{T}$. As in the previous cross-sectional regressions, I control for the book-to-market ratio, market capitalization, R&D intensity, the past month performance and dummy variables to control for industry fixed-effects at the 1-digit SIC level.

skilled workers. This result is consistent with the theoretical model, firms that rely more heavily on high-skilled workers are more exposed to volatility fluctuations because their labor is more costly to adjust.

1.2.5 Reliance on Skilled Labor Premium as a Risk Factor

The results presented in the previous section suggest that the reliance on skilled labor risk premium must contain information about systemic risk, in particular, information about aggregate volatility risk. To corroborate this conclusion, I first explore the relationship of the reliance on skilled labor risk premium and existing risk factors. Then, I explore whether the reliance on skilled labor risk premium is able to explain the cross-sectional variation in average excess equity returns on 48 industry portfolios from Kenneth French's data library. Fama and French show that industry portfolios are particularly challenging to explain for both the CAPM and their three-factor model.

First, I run a regression of the spread in returns between the top and bottom quintiles of portfolios sorted on the reliance on skilled labor index (rp_t) on the market excess return (MKT), the size risk factor (SMB), and the book to market risk factor (HML) to check if the reliance on skilled labor premium remains significant after taking into account the well known Fama-French risk factors. The estimated coefficients and Newey-West standard errors are,

$$rp_t = \underset{(0.230)}{0.591} + \underset{(0.062)}{0.148}\,\text{MKT}_t + \underset{(0.082)}{0.250}\,\text{SMB}_t - \underset{(0.093)}{0.925}\,\text{HML}_t + u_t$$

The results indicate that the intercept remains positive and statistically significant and cannot be explained by the three Fama-French risk factors suggesting that the reliance on skilled labor risk premium contains independent information about the cross-section of average equity returns. Similar conclusions arise if I only control for the market excess return (MKT), and if I use the risk premium generated by the workers' skill index from Fama and MacBeth estimates.

If the reliance on skilled labor premium is not spanned by known risk factors, it is still a question wether it contains information about systemic risk. Therefore, I explore whether the reliance on skilled labor premium is able to explain the cross-sectional variation in average excess equity returns on 48 industry portfolios. Based on the previous results one would expect that it has information beyond that of the market excess return, the size risk factor, and the book to market risk factor. Consider the following specification for any portfolio p's return,

$$E(r_{p,t}) = \lambda_0 + \sum_{i=0}^{I} \beta_{p,i}\lambda_i \tag{1.17}$$

where $r_{i,t}$ is the equity return in excess of the risk-free rate, $\beta_{p,i}$ is the asset p's exposure to risk factor i, and λ_i is the corresponding market price of risk. Following the standard cross-sectional regression techniques, I first run a time-series regression of each portfolio equity excess returns on the risk factors and obtain $\beta_{p,i}$. Then, I run a cross-sectional regression with the estimated betas. Figure presents the fitted and observed excess returns for three different models. The upper panel is the standard CAPM which uses the market excess return as risk factor, the panel in the middle uses the market excess return, the size risk factor, and the book to market risk factor, and the lower panel uses the market excess return and the workers' skill premium as risk factors. The adjusted R^2s suggest that the workers' skill premium contains important information about the spread in excess returns. When the basic CAPM is augmented with the workers' risk premium the adjusted R^2 increases to 40.2% from -1.2%. Moreover, the adjusted R^2 is twice the size of the Fama-French three factor model.

1.3 Conclusion

This essay shows that investors demand higher expected returns for holding stocks of firms with a high reliance on skilled labor relative to stocks of firms with a low reliance on skilled labor. Firms with a high reliance on skilled labor are more risky because they are more exposed to fluctuations in aggregate uncertainty.

First, I present a production-based asset pricing model with two important ingredients. First, firms face adjustment costs in labor are increasing with the skill of the worker. Second, aggregate productivity growth has time-varying volatility and the stochastic discount factor to compute asset prices comes from the the long-run risks model of Bansal and Yaron. The model shows that a rise in aggregate uncertainty rises the cost of capital as well as cautiousness in hiring and firing. This effect will be larger at firms with a high share of skilled workers because their labor is more costly to adjust. As a result, firms with a high reliance on skilled labor are more exposed to fluctuations in aggregate uncertainty and investors command a higher return for investing in this type of firms.

Consistent with the implications of the model, I present empirical evidence suggesting that firms which have a high concentration of employment that require high levels of skill have higher expected returns on equity than those in which a larger share of their occupations need little or no skills. Moreover, the risk premium for a firm's reliance on skilled labor is larger in times of high uncertainty than in times of low uncertainty. These conclusions are robust to whether I include controls for known characteristics that explain the cross-section of expected returns, and to alternative empirical strategies.

1.4 Tables and Figures

Table 1.1: Labor Adjustment Costs Summary Statistics

Variable	No. obs.	Overall Mean	Overall Std. Dev.	By education <12 yrs.	By education >12 yrs.
% firms with a newly hired	5269	0.69	0.46	—	—
Newly hired employee					
Age	3612	27.34	10.00	25.56	27.63
Relevant experience (months)	3437	45.53	67.76	36.19	49.57
Time recruiting for position (days)	2487	18.07	37.30	12.05	22.24
No. of persons interviewed for position	3606	4.63	8.85	3.27	5.50
Hrs. spent training by employees	3514	13.33	22.46	10.17	15.95
Hrs. spent training by superiors	3537	19.62	25.54	17.87	22.80
Hrs. spent training by employees and superiors	3473	32.82	37.06	27.98	38.61
Productivity gap	3568	15.69	18.82	12.72	17.83
Max wage for position US$/hour	2558	5.57	2.63	4.69	5.89

Notes: Table 1.1 presents summary statistics for the firm-level data from the 1980 Employer Opportunity Pilot Project (EOPP). The data corresponds to firms that had a recent new hire at the time of the interview.

Table 1.2: Labor Adjustment Costs and Education Level

	Dependent Variable			
	Days recruiting	No. interviewed	Hrs. training	Productivity gap
Education (1=HS or more)	7.029***	1.491***	5.940***	4.001***
	(1.372)	(0.371)	(1.598)	(1.185)
Age	0.162	-0.016	-0.018	-0.056
	(0.098)	(0.022)	(0.073)	(0.051)
Experience	-0.002	0.001	-0.055***	-0.010
	(0.015)	(0.003)	(0.014)	(0.008)
Sex (1=male)	1.156	-1.083**	-0.811	-1.899*
	(2.179)	(0.418)	(1.430)	(1.068)
Size	0.355	0.164	0.634*	0.028
	(0.381)	(0.113)	(0.359)	(0.141)
N	2336	3338	3238	3318

Notes: Table 1.2 presents the estimated coefficients from a regression of several components of labor adjustment costs on the level of education, age, gender and relevant experience of the recent new hire, and the size of the establishment. The regressions also include unreported dummy variables to control fixed industry characteristics at the 3-digit SIC level. Education is a dummy variable equal to 1 when the newly hired has a high-school diploma or more education, experience is relevant job experience in months, sex is a dummy variable that equals to 1 if the newly hired is male, size is the number of workers in hundreds, and the last new hire productivity gap is the productivity of the last employee in the position minus the productivity of the new employee. Standard errors clustered at the 3-digit SIC are reported in parenthesis. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively.

Table 1.3: Labor Adjustment Costs and Wages

	Dependent Variable			
	Days recruiting	No. interviewed	Hrs. training	Productivity gap
ln Wage	14.635***	1.968***	17.849***	4.768***
	(3.388)	(0.640)	(3.810)	(1.738)
Age	0.087	-0.003	-0.012	-0.077
	(0.106)	(0.030)	(0.079)	(0.075)
Experience	-0.017	-0.003	-0.072***	-0.010
	(0.016)	(0.003)	(0.015)	(0.010)
Sex [1=male]	-3.038	-1.794***	-3.232*	-3.511**
	(2.936)	(0.487)	(1.669)	(1.361)
Size	0.336	0.158	0.430	-0.020
	(0.387)	(0.118)	(0.364)	(0.160)
N	1669	2360	2292	2343

Notes: Table 1.3 presents the estimated coefficients from a regression of several components of labor adjustment costs on the top hourly wage for that position, the age, gender and relevant experience of the recent new hire, and the size of the establishment. The regressions also include unreported dummy variables to control fixed industry characteristics at the 2-digit SIC level. Experience is relevant job experience in months, sex is a dummy variable that equals to 1 if the newly hired is male, size is the number of workers in hundreds, and the last new hire productivity gap is the productivity of the last employee in the position minus the productivity of the new employee. Standard errors clustered at the 3-digit SIC are reported in parenthesis. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively.

Table 1.4: Calibration

Parameter	Definition	Value	Source
α	Labor share	0.4	Labor share in the data
λ	Relative efficiency of skilled workers	2	
ζ	Worker's compensation parameter	2.88	Cooper and Willis
μ	Aggregate technology consumption	0.0015	Bansal et al.
ρ	Technology growth persistence	0.975	Bansal et al.
χ^1	Linear cost of adjusting skilled labor	6-months wage	Parsons
χ^2	Linear cost of adjusting unskilled labor	1/4-month wage	Cooper and Willis
β	Subjective discount factor	0.9989	Bansal et al.
γ	Risk aversion	10	Bansal et al.
ψ	Intertemporal elasticity of substitution	2	Bansal et al.

Table 1.5: Reliance on Skilled Labor for Selected Industries

	Reliance on Skilled Labor Index		
Industry	1998-2010	1988-1999	2000-2010
Highest Reliance on Skilled Labor			
Engineering and architectural services	3.568	3.564	3.571
Colleges and universities	3.551	3.402	3.638
Legal services	3.550	3.581	3.532
Research and testing services	3.380	3.400	3.368
Guided missiles, space vehicles parts	3.368	3.302	3.418
Offices of health practitioners	3.364	3.383	3.319
Hospitals	3.362	3.365	3.360
Offices and clinics of medical doctors	3.341	3.300	3.365
Computer and data processing services	3.269	3.470	3.152
Accounting, auditing and bookkeeping	3.267	3.350	3.233
Lowest Reliance on Skilled Labor			
Crop services	1.794	1.712	1.815
Meat products	1.782	1.721	1.827
Laundry, cleaning and garment services	1.749	1.692	1.783
Logging	1.741	1.759	1.708
Grocery stores	1.734	1.801	1.684
Hotels and motels	1.710	1.737	1.694
Manufacturing women's outerwear	1.635	1.547	1.702
Manufacturing men's suits and coats	1.571	1.444	1.665
Gasoline service stations	1.540	1.810	1.338
Eating and drinking places	1.486	1.384	1.562
Automobile parking	1.485	1.468	1.499
Services to buildings	1.355	1.368	1.347

Table 1.6: Summary Statistics for Financial Variables

Variable	Mean	Std. Dev.
Reliance on skilled labor (LSKILL)	2.668	0.448
log Book-to-Market equity (lnBM)	-0.717	0.967
log Market equity (lnME)	5.311	2.124
R&D intensity (R&D)	0.045	0.129
Operating leverage (OPLEV)	1.085	0.918
Earnings(+)/Assets (E/A+)	0.078	0.081
Investment rate (ASSETG)	0142	0 .395
Sales Beta (SALESB)	2.088	3.759
Labor Intensity (LABINT)	0.010	0 .034
Leverage (LEV)	0.346	0.225

Notes: Table 1.6 presents summary the sample mean and standard deviation of the variables used in the empirical section. The reliance on skilled labor index (LSKILL) is computed using the definition in (1.12), R&D intensity (R&D) is easured as R&D expenditures as a share of the firm's market equity, operating leverage (OL) is measured as the ratio of operating costs to total assets value, profitability (E/A+) is measured as positive earnings before interest divided by total assets, assets growth (ASSETG) is defined as the annual growth in asset value, sales beta (SALESB) is measured as the slope coefficient from a regression of a firm's annual growth in sales on annual GDP growth using quarterly data, labor intensity (LABINT) is defined as the ratio of number of employees to total assets value, and total leverage (LEV) is measured as the ratio of book liabilities (total assets minus book equity) to total market value of firm (market equity plus total assets minus book equity). The sample covers the period 1987–2011

Table 1.7: Monthly Excess Returns on Portfolios Sorted on the Reliance on Skilled Labor Index

Panel A: Equally-Weighted Portfolios

	Reliance on Skilled Labor Quintile				
	1 (Low)	2	3	4	5 (High)
Excess returns	0.547	0.751	0.832	0.933	1.044
Test of Monotonicity for Excess Returns (p-values)					
	High minus Low	t–test	MR–test	MR^{all}–test	Wolak–test
	0.497	0.078	0.010	0.010	0.957

Panel B: Value-Weighted Portfolios

	Reliance on Skilled Labor Quintile				
	1 (Low)	2	3	4	5 (High)
Excess returns	0.452	0.548	0.567	0.524	0.761
Test of Monotonicity for Excess Returns (p-values)					
	High minus Low	t–test	MR–test	MR^{all}–test	Wolak–test
	0.309	0.138	0.068	0.067	0.942

Notes: Table 1.7 presents monthly excess returns on five portfolios sorted on the reliance on skilled labor index along with the tests for monotonicity proposed in Patton and Timmermann and Wolak. For both equally-weighted and value-weighted portfolios, the lower panel reports the difference in returns between the top and bottom quintiles along with the associated p–value of the t-statistic for this spread computed using Newey-West standard errors. The table also reports the p–values from the Patton and Timmermann monotonicity relation tests, MR–test and MR^{all}–test, and from the Wolak test. The MR–test and MR^{all}–test null hypothesis is that the excess returns across portfolios are identical or weakly declining against the alternative hypothesis of a strictly increasing pattern. The Wolak test's null hypothesis is that a weakly monotonic relation exists between returns and the sorting variable, while the alternative hypothesis contains the case of no such monotonic relation. Excess returns are monthly and expressed in percentage terms. The sample covers July 1988 to June 2011.

Table 1.8: Monthly Equity Returns and Reliance on Skilled Labor Index

	Dependent Variable: Monthly Excess Returns					
Explanatory Variable	(1)	(2)	(3)	(4)	(5)	(6)
LSKILL	0.448***	0.629***	0.445***	0.592***	0.356***	0.257*
	(0.067)	(0.080)	(0.070)	(0.074)	(0.074)	(0.139)
lnBM		0.486***		0.391***	0.377***	0.203
		(0.043)		(0.041)	(0.045)	(0.127)
lnME			-0.198***	-0.139***	-0.069***	0.038
			(0.025)	(0.025)	(0.023)	(0.056)
r_{01}	-0.012***	-0.013***	-0.012***	-0.013***	-0.005	0.057***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.009)
$N \times T$	695,367	695,367	695,367	695,367	694,547	45,703
N	10,890	10,890	10,890	10,890	10,890	312

Notes: Columns (1)–(4) of Table 1.8 present the estimated coefficients from a regression of firm-level monthly stock returns on the workers' skill index, namely,

$$r_{ij,t+1} = \alpha + \beta_1 \text{LSKILL}_{j,t} + \mathbf{x}'_{ij,t}\gamma + u_{ij,t+1}$$

where r_{ij} is the monthly stock return of firm i from industry j in excess of the risk-free rate, and LSKILL_j is the reliance on skilled labor index at industry j. Industry membership j is defined by the firm's 3-digit SIC code and it is used to match the firm with its corresponding workers' skill index. The vector $\mathbf{x}$ includes controls for the (log) book-to-market equity ratio (lnBM), (log) market equity (lnME), past one-month equity excess return (r_{01}). Column (5) presents the estimated value-weighted coefficients from a regression of firm-level monthly stock returns on the workers' preparation index where the weights are given by market capitalization. Column (6) presents the estimated coefficients from a regression of industry-level monthly stock returns on the workers' skill index where industry membership is defined by the firm's 3-digit SIC code. All regressions control for industry fixed-effects at the 1-digit SIC level, and year fixed-effects. Stock returns are monthly and expressed in percentage terms. The sample covers Jan-1987 to June-2011. Standard errors clustered at the 3-digit SIC are reported in parenthesis. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively.

Table 1.9: Robustness to Additional Controls

	Dependent Variable: Firm Equity Returns						
Explanatory Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
LSKILL	0.304***	0.335***	0.380***	0.419***	0.328***	0.329***	0.279***
	(0.090)	(0.090)	(0.090)	(0.082)	(0.079)	(0.080)	(0.085)
lnBM	0.383***	0.412***	0.427***	0.258***	0.155***	0.161***	0.141***
	(0.034)	(0.036)	(0.038)	(0.039)	(0.045)	(0.046)	(0.050)
lnME	-0.118***	-0.091***	-0.133***	-0.120***	-0.157***	-0.153***	-0.150***
	(0.024)	(0.024)	(0.026)	(0.020)	(0.018)	(0.018)	(0.019)
R&D	2.234***	2.216***	2.396***	1.983***	2.211***	2.144***	2.901***
	(0.493)	(0.532)	(0.561)	(0.558)	(0.637)	(0.631)	(0.461)
OPLEV		0.300***	0.275***	0.180**	0.086**	0.096**	0.080**
		(0.071)	(0.073)	(0.089)	(0.040)	(0.040)	(0.039)
E/A+			2.332***	1.864***	1.456***	1.433***	1.439***
			(0.455)	(0.464)	(0.441)	(0.446)	(0.464)
ASSETG				-1.031***	-0.857***	-0.857***	-0.850***
				(0.099)	(0.075)	(0.079)	(0.081)
SALESB					0.018**	0.018**	0.018**
					(0.008)	(0.008)	(0.008)
LABINT						-0.670**	-0.656**
						(0.322)	(0.316)
LEV							0.098
							(0.187)
r_{01}	-0.014***	-0.013***	-0.013***	-0.012***	-0.010***	-0.010***	-0.011***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
$N \times T$	695,367	687,192	684,161	628,367	525,501	519,692	510,664

Notes: Table 1.9 presents the estimated coefficients from a regression of firm-level monthly stock returns on the workers' skill index, namely,

$$r_{ij,t+1} = \alpha + \beta_1 \text{LSKILL}_{j,t} + \mathbf{x}'_{ij,t}\gamma + u_{ij,t+1}$$

where r_{ij} is the monthly stock return of firm i from industry j in excess of the risk-free rate, and LSKILL_j is the reliance on skilled labor index at industry j. Industry membership j is defined by the firm's 3-digit SIC level and it is used to match the firm with its corresponding workers' skill index. The vector $\mathbf{x}$ includes controls for the (log) book-to-market equity ratio (lnBM), (log) market equity (lnME), past one-month excess returns r_{01}, R&D intensity (R&D), profitability (E/A+), assets growth (ASSETG), sales beta (SALESB), labor intensity (LABINT), and leverage (LEV). All regressions control for industry fixed-effects at the 1-digit SIC level and year fixed-effects. Stock returns are monthly and expressed in percentage terms. The sample covers Jan-1987 to June-2011. Standard errors clustered at the 3-digit SIC are reported in parenthesis. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively.

Table 1.10: Reliance on Skilled Labor Premium and Aggregate Volatility: Panel Data Evidence

	Dependent Variable: Firm Equity Returns					
Explanatory Variable	(1)	(2)	(3)	(4)	(5)	(6)
LSKILL × VXO index	0.745***		0.661***		0.442**	
	(0.241)		(0.212)		(0.172)	
LSKILL × S&P500 RVOL		0.429***		0.386***		0.271***
		(0.164)		(0.141)		(0.099)
LSKILL	0.088	0.084	0.220**	0.203**	0.102	0.063
	(0.131)	(0.119)	(0.102)	(0.098)	(0.092)	(0.095)
lnBM	0.572***	0.568***	0.456***	0.453***	0.322***	0.316***
	(0.039)	(0.038)	(0.048)	(0.048)	(0.050)	(0.051)
lnME	-0.061**	-0.049*	-0.068***	-0.053**	-0.100***	-0.087***
	(0.024)	(0.026)	(0.021)	(0.022)	(0.019)	(0.019)
R&D	2.945***	3.029***	2.542***	2.601***	3.434***	3.485***
	(0.494)	(0.497)	(0.554)	(0.558)	(0.422)	(0.422)
OPLEV			0.163*	0.165*	0.066*	0.068*
			(0.088)	(0.088)	(0.038)	(0.038)
E/A+			2.596***	2.551***	2.336***	2.237***
			(0.448)	(0.421)	(0.398)	(0.388)
INVR			-1.180***	-1.182***	-1.012***	-1.015***
			(0.093)	(0.092)	(0.069)	(0.070)
SALESB					0.018**	0.022***
					(0.007)	(0.007)
LABINT					-1.241***	-1.543***
					(0.463)	(0.587)
LEV					0.255	0.230
					(0.171)	(0.174)

Notes: Table 1.10 presents the estimated coefficients from a regression of firm-level monthly stock returns on the workers' skill index $\text{WSKILL}_{j,t}$ and its interaction with aggregate volatility σ, namely,

$$r_{ij,t+1} = \alpha + (\beta_1 + \beta_2 \sigma_t) \times \text{LSKILL}_{j,t} + \mathbf{x}'_{ij,t}\gamma + \beta_3 \sigma_t + u_{ij,t+1}$$

where r_{ij} is the monthly stock return of firm i from industry j in excess of the risk-free rate. Industry membership j is defined by the firm's 3-digit SIC level and it is used to match the firm with its corresponding workers' skill index. Aggregate volatility is approximated as the implied volatility computed using the VXO index based on S&P 100 index options (VXO index), and the realized volatility computed as the monthly standard deviation of the daily S&P 500 index (S&P500 RVOL). Both measures are standardized. The sample covers Jan-1987 to June-2011. Standard errors clustered at the 3-digit SIC are reported in parenthesis. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively.

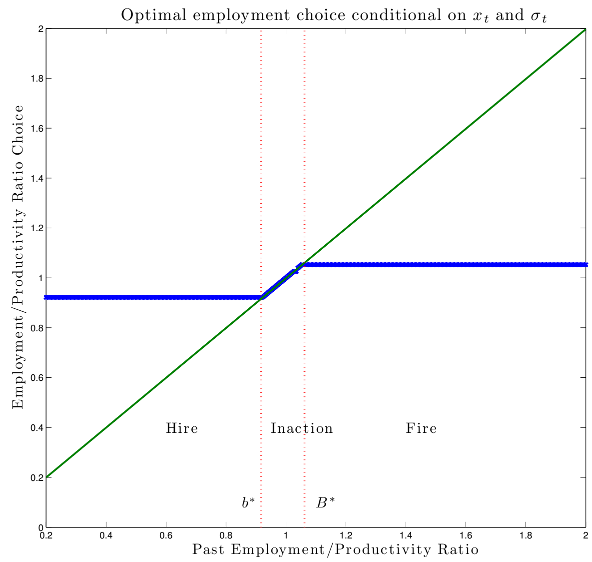
Table 1.11: Reliance on Skilled Labor Premium and Aggregate Volatility: Time Series Evidence

	Dependent Variable: Workers' Skill Premium							
Explanatory Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VXO index	0.506**	0.546**	0.624*	0.707**				
	(0.226)	(0.223)	(0.324)	(0.318)				
S&P500 RVOL					0.278*	0.308**	0.356*	0.422**
					(0.158)	(0.155)	(0.213)	(0.209)
YIELD3M		0.067		0.154		0.034		0.115
		(0.096)		(0.150)		(0.097)		(0.151)
TERMSPRD		-0.105		-0.074		-0.160		-0.142
		(0.202)		(0.330)		(0.206)		(0.331)
Constant	0.509**	0.441	0.523	0.069	0.434*	0.582	0.427	0.225
	(0.230)	(0.666)	(0.347)	(1.041)	(0.226)	(0.700)	(0.337)	(1.067)
T	275	275	275	275	275	275	275	275

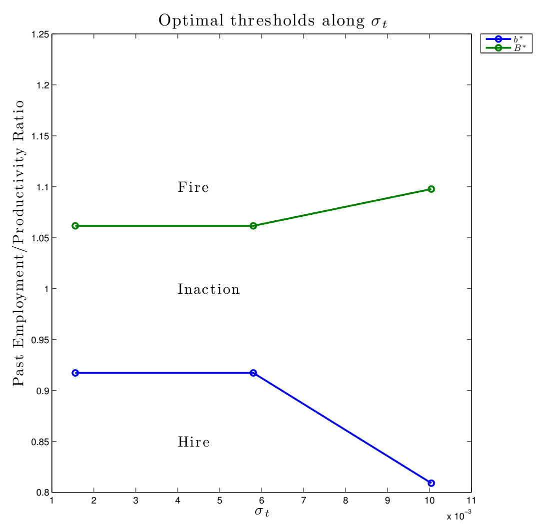
Notes: Table 1.11 presents the estimated coefficients a regression of the time-series risk premia generated by the reliance on skilled labor rp on aggregate uncertainty, namely,

$$rp_{t+1} = \alpha + \beta_1 \sigma_t + \mathbf{x}_t' \beta + u_{t+1} \quad (1.18)$$

where $\mathbf{x}$ includes the dividend yield (dp_t), the 3-month Treasury bill rate (y_t^{3m}), and the premium between the 10-year Treasury bond and a 3-month Treasury bill ($y_t^{10y} - y_t^{3m}$). In Columns (1)–(2) and (5)–(6) the reliance on skilled labor premium is obtained from Fama and MacBeth estimates of equation (1.15) where I control for the book-to-market ratio, market capitalization, R&D intensity, past performance and dummy variables to control for industry fixed-effects at the 1-digit SIC level. In Columns (3)–(4) and (7)–(8) the reliance on skilled labor premium is computed as the spread of returns between the top and bottom quintiles of portfolios sorted on the reliance on skilled labor index. The estimates consider as a measure of aggregate uncertainty the implied volatility computed using the VXO index based on S&P 100 index options (VXO index) and the realized volatility computed as the monthly standard deviation of the daily S&P 500 index (S&P500 RVOL). The sample covers July 1988 to June 2011. Newey-West standard errors are reported in parenthesis. The 1%, 5%, and 10% significance levels are denoted with ***, **, and *, respectively.



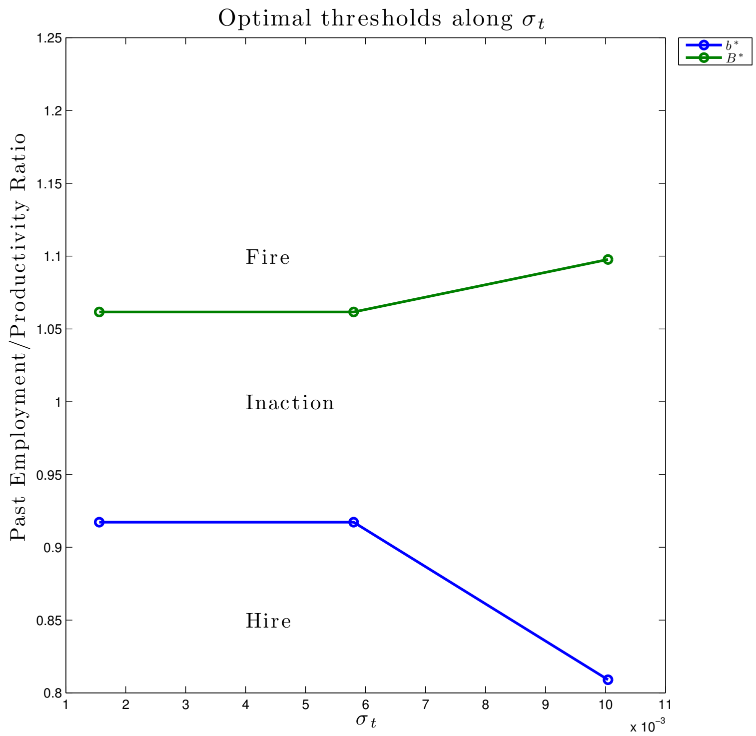
(a) Optimal employment choice



(b) Impact of uncertainty on the optimal inaction region

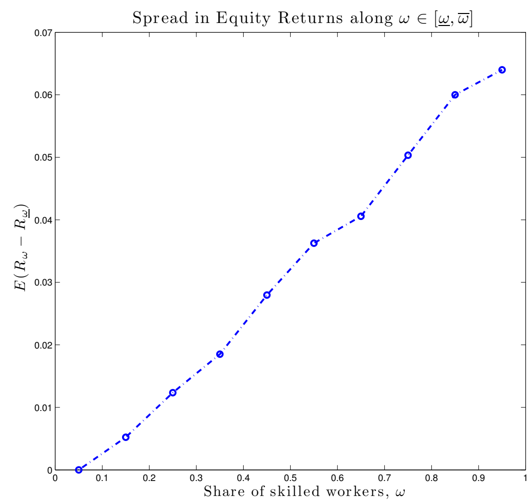
Notes: Panel (a) of Figure 1.1 displays the optimal choice of labor-aggregate productivity ratio $\tilde{n}_{i,t}$ along with the optimal inaction region $(b^*(x_t, \sigma_t), B^*(x_t, \sigma_t))$ for $(x_t, \sigma_t) = (0, \sigma_2)$. The labor-aggregate productivity ratio is defined as $\frac{n_{i,t}}{A_t^{1/(1-\alpha)}}$. Panel (b) displays the impact of aggregate uncertainty σ_t on the optimal inaction region $(b^*(x_t, \sigma_t), B^*(x_t, \sigma_t))$ for $x_t = 0$.

Figure 1.1: Optimal Employment Choice

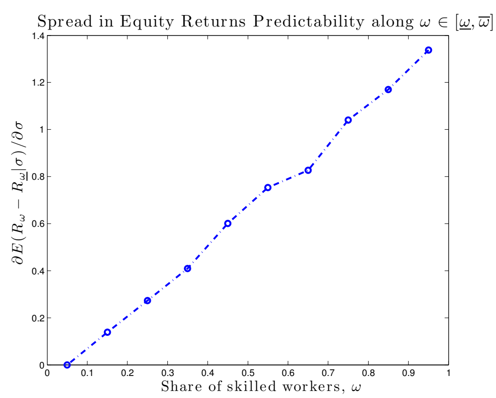


Notes: Figure 1.2 displays the impact of aggregate uncertainty σ_t on the optimal inaction region $(b^*(x_t, \sigma_t), B^*(x_t, \sigma_t))$ and the optimal returning points $q^*(x_t, \sigma_t)$ and $Q^*(x_t, \sigma_t)$ for $x_t = 0$.

FIGURE 1.2: Impact of Uncertainty on the Optimal Inaction Region



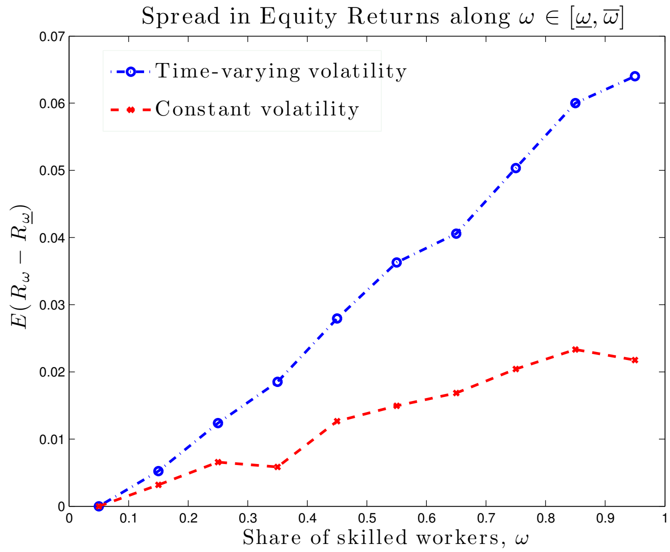
(a) Average equity returns in excess of the return on the firm with the lowest ω



(b) Change in expected equity returns in excess of the return on the firm with the lowest ω when uncertainty increases one standard deviation

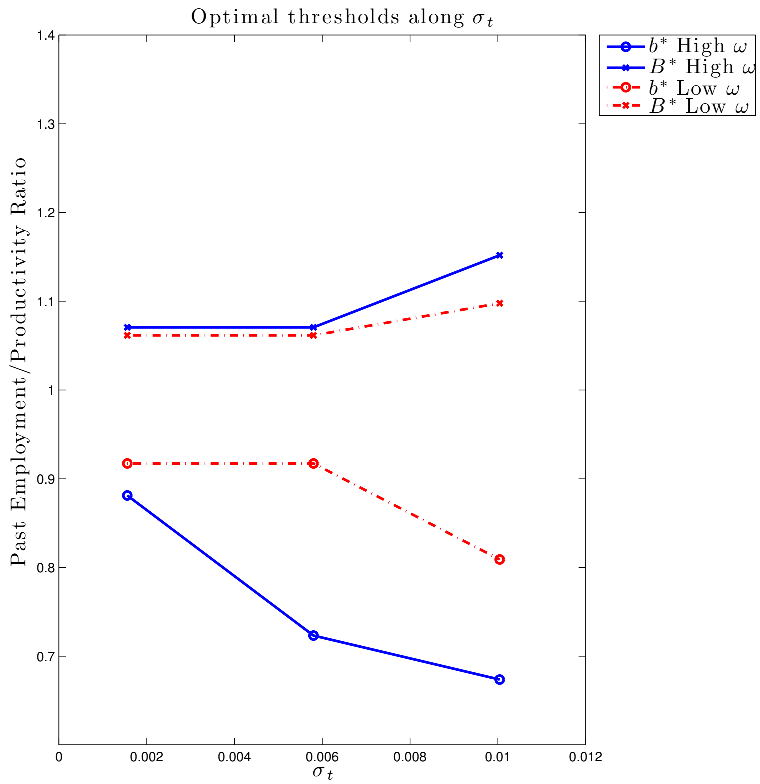
Notes: Panel (a) of Figure 1.3 displays the average equity returns on a firm with a share of skilled workers ω in excess of the return on the firm with the lowest ω, $E(R_\omega - R_{\underline{\omega}})$, for different values of ω. Panel (b) of Figure 1.3 displays the change in expected equity returns in excess of the return on the firm with the lowest ω when uncertainty increases one standard deviation, $\partial E(R_\omega - R_{\underline{\omega}}|\sigma_t)/\partial\sigma$.

FIGURE 1.3: Model's Implications for The Cross-section of Expected Equity Returns



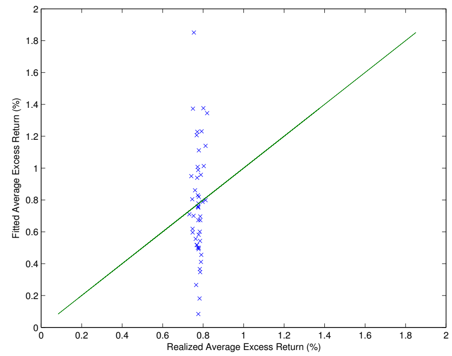
Notes: Figure 1.4 displays the expected equity return on a firm with a share of skilled workers ω in excess of the return on the firm with the lowest ω. The line with circular markers comes from the baseline model assuming time-varying aggregate volatility. The line with cross markers corresponds to the case in which aggregate volatility is constant.

FIGURE 1.4: Expected Equity Returns Under Alternative Investor's Preferences

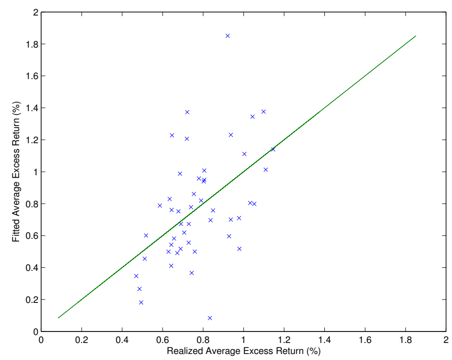


Notes: Figure 1.5 displays the optimal inaction region $(b^*(x_t, \sigma_t), B^*(x_t, \sigma_t))$ for a firm with a high share of low-skilled workers (low-ω) and one with a high share of high-skilled workers (high-ω).

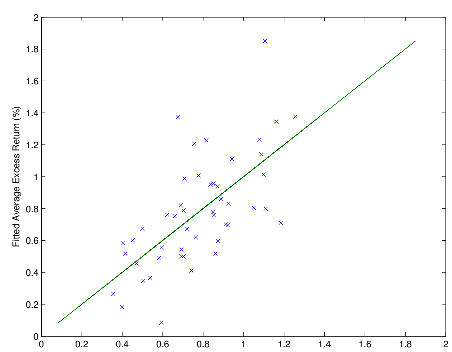
Figure 1.5: Optimal Inaction Region Across Firms



(a) CAPM, adj-$R^2 = -1.2\%$



(b) Fama and French three-factor model, adj-$R^2 = 20.4\%$



(c) CAPM with reliance on skilled labor premium, adj-$R^2 = 40.2\%$

FIGURE 1.6: 48 Industry Portfolios: Realized Average Returns vs. Fitted Average Returns

2

Temperature, Aggregate Risk, and Expected Returns

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 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

[1] Impacts on labor productivity are discussed in Huntington (1915), Crocker and Horst (1981), Meese et al. (1982); Curriero et al. (2002), Gallup and Sachs (2001) provide evidence on negative impacts on human capital through health; Jacob et al. (2007) provide evidence on crime and social unrest. More recently, Dell et al. (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.

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 et al. (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 et al. (2005a), 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 2.1 documents the key empirical regularities. Section 3.2 presents the LRR-T model, and discusses its theoretical and quantitative implications for asset markets. Conclusions follow.

[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 et al. (2009), for cross-sectional differences in expected returns see Bansal et al. (2005a) and Hansen et al. (2008), and for option prices see Drechsler and Yaron (2009).

2.1 Temperature Risk, Expected Equity Returns, and Economic Growth

2.1.1 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 (2007b)). 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 port-

[3] To compute large-scale spatial means, each station is associated to a grid point of a $5^\circ \times 5^\circ$ 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.

folio, 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 et al. (2009) (Penn World 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.2 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 3.1 presents summary statistics for temperature dynamics, annual world GDP and consumption per capita growth. The average global temperature is 14°C, 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 3.1 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

[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.

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 2.2 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 furthest away from the Equator.

2.1.2 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,

$$E(R_{i,t}) = \lambda_0 + \beta_{i,w}\lambda_w \tag{2.1}$$

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,

$$R_{i,t} = \beta_{i,0} + \beta_{i,w}\Delta w_t + \varepsilon_{i,t} \tag{2.2}$$

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 (2.1), that is, performing a cross-sectional regression of the average return on a constant and the estimated temperature beta for each portfolio.

Figure 2.1 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,

$$R_{i,t} = \varsigma_i + (\beta_0 + \beta_1 \times \ell_i)\Delta w_t + \varepsilon_{i,t} \tag{2.3}$$

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 2.3 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 2.4 presents the estimated coefficients from the following fixed-effect model,

$$R_{i,t} = \varsigma_i + \left(\beta_0 + \sum_{j=2}^{4} \beta_j \times \mathbf{I}(\ell_i \in g_j) \right) \Delta w_t + \varepsilon_{i,t} \tag{2.4}$$

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 2.4 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 2.5 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 (2.4). Panel A of Table 2.6 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.

2.1.3 Distance to the Equator and Temperature Sensitive Sectors

The empirical evidence presented in Section 2.1.2 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 2.2, 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 2.3 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,

$$ER_{i,t} = \beta_{i,0} + \beta_{i,h} ER_t^H + \varepsilon_{i,t} \tag{2.5}$$

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 2.4 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

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

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 (2007b)). 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.

2.1.4 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 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 2.7 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,

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + \beta_0 \zeta_t + \varepsilon_{i,t} \tag{2.6}$$

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 2.8 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

[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.

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 2.8 presents the results of running a similar regression as in (2.6) 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 2.9 extends our baseline growth model (2.6) by adding the interaction between temperature shocks and the distance to the Equator as an explanatory variable, namely,

$$\Delta y_{i,t} = \varsigma_i + \rho \Delta y_{i,t-1} + \alpha_0 w_{t-1} + (\beta_0 + \beta_1 \times \ell_i)\zeta_t + \varepsilon_{i,t} \tag{2.7}$$

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 2.8 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 2.5 plots the response to a one-standard deviation shock to temperature of GDP growth in Ghana, a country close to the Equator $\ell_i = 0.07$, 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 et al. (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 et al. (1982)), human capital through health (Curriero et al. (2002), Gallup and Sachs (2001)), crime and social unrest (Jacob et al. (2007)). More recently, Dell et al. (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 et al. (2005a), we explore if countries closer to the Equator have a higher exposure to long-run aggregate growth. Table

2.10 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 et al. (2005a), 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.

2.2 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.

2.2.1 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,

$$V_t = \left[(1-\delta)C_t^{\frac{1-\gamma}{\theta}} + \delta\Big(E_t\big[V_{t+1}^{1-\gamma}\big]\Big)^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}, \tag{2.8}$$

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),

$$m_{t+1} = \theta \ln \delta - \frac{\theta}{\psi}\Delta c_{t+1} + (\theta - 1) r_{c,t+1} \tag{2.9}$$

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,

$$E_t[\exp(m_{t+1} + r_{j,t+1})] = 1 \tag{2.10}$$

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

2.2.2 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, 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,

$$\Delta c_{t+1} = \mu_c + x_t + \sigma\eta_{t+1} \tag{2.11}$$

$$x_{t+1} = \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma\varphi_e e_{t+1} \tag{2.12}$$

$$w_{t+1} = \mu_w + \rho_w(w_t - \mu_w) + \sigma_\zeta \zeta_{t+1} \tag{2.13}$$

$$\Delta d_{t+1} = \mu_d + \phi x_t + \pi\sigma\eta_{t+1} + \varphi_u \sigma u_{t+1} \tag{2.14}$$

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]

2.2.3 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 (2.9). We start by solving for the unobservable return on wealth $r_{c,t+1}$ (the return on the consumption claim), which

[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.

we approximate using the log-linearization of returns as proposed in Bansal et al. (2007a).

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

$$r_{c,t+1} = \kappa_0 + \kappa_1 z_{c,t+1} + \Delta c_{t+1} - z_{c,t}, \tag{2.15}$$

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

$$z_{c,t} = A_0 + A_x x_t \tag{2.16}$$

where A_x must satisfy,[8]

$$A_x = \frac{1 - \frac{1}{\psi}}{1 - \kappa_1 \rho} \tag{2.17}$$

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

$$m_{t+1} = m_0 + m_x x_t - \lambda_\eta \sigma \eta_{t+1} - \lambda_e \sigma e_{t+1} - \lambda_\zeta \sigma_\zeta \zeta_{t+1} \tag{2.18}$$

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

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 B.

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 (2.18), the risk premium on any asset with continuous return $r_{j,t+1}$ is given by,

$$E_t\left(r_{j,t+1} - r_{f,t} + \frac{1}{2}V_t(r_{j,t+1})\right) = \beta_{j,\eta}\lambda_\eta\sigma^2 + \beta_{j,x}\lambda_e\sigma^2 + \beta_{j,\zeta}\lambda_\zeta\sigma_\zeta^2 \qquad (2.19)$$

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 the IES is larger than one. Figure 3.2 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 (2.19) 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 (2.14). Figure 2.7 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

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

[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.

value) leading to an increase in the risk compensation from this source of risk.

2.2.4 Calibration

Table 2.11 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 et al. (2007a). 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 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,

$$\Delta d_{i,t+1} = \mu_{i,d} + \phi_i x_t + \pi_i \sigma \eta_{t+1} + \varphi_{i,u} \sigma u_{i,t+1} \tag{2.20}$$

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.

2.2.5 Model Quantitative Implications

Our calibration of the model is chosen to match the bivariate dynamics of consumption and temperature quite well. Table 2.12 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 2.13 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 2.12).

Table 2.14 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 2.14 presents the risk premium on the levered asset, computed using the expression (2.19), 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 2.15 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.

2.3 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.

2.4 Tables and Figures

Table 2.1: 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)

Notes: Table 3.1 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.

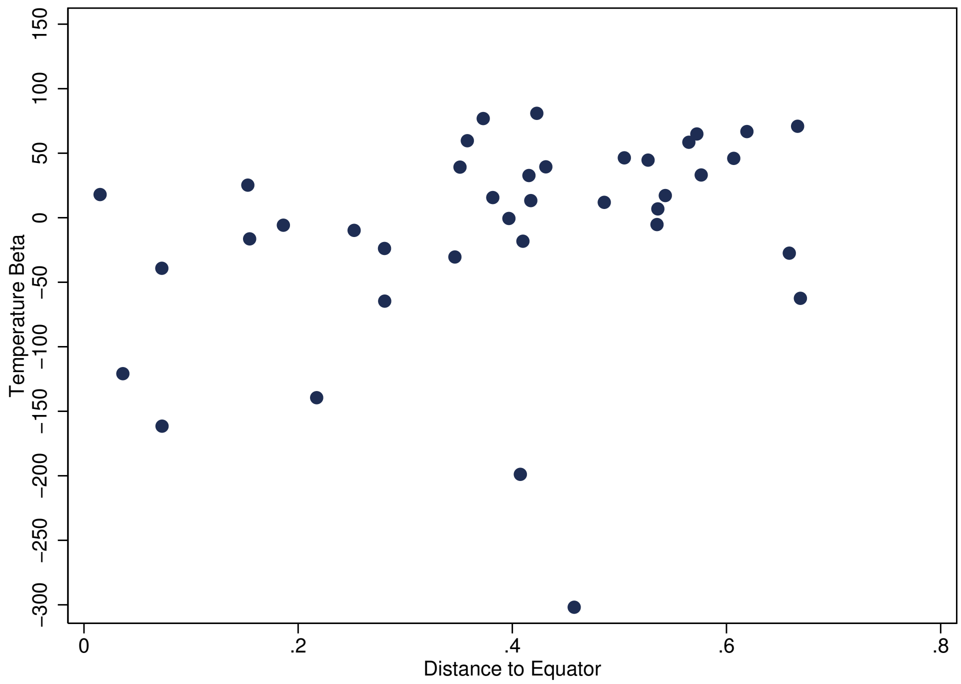


Figure 2.1 presents a scatter plot for the estimated temperature beta against the distance to the Equator for a sample of 38 countries. The value of the temperature beta is obtained by regressing the market real return for each country on the change in global temperature. The distance from the equator 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 2.2.

Figure 2.1: Temperature Beta and Distance to the Equator

Table 2.2: 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

Notes: Table 2.2 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 2.3: 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

Notes: The first column of Table 2.3 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 2.4: 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

Notes: Table 2.4 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 2.3. The data is annual, and market equity returns are real and expressed in percentage terms.

Table 2.5: 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)	

Notes: Table 2.5 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 2.6: 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 2.6 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 2.3, where global temperature is modelled as a first-order autoregressive process. Panel B of Table 2.6 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 2.7: 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)

Notes: Table 2.7 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 2.8: 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

Notes: Table 2.8 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 2.9: 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

Notes: Table 2.9 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 2.10: 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

Notes: Table 2.10 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 2.11: 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		

Notes: Table 2.11 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 2.12: Model Implied Dynamics of Growth Rates and Returns

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		

Notes: Table 2.12 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 2.13: 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

Notes: Table 2.13 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 2.14: 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

Notes: Table 2.14 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 2.15: 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

Notes: Table 2.15 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.

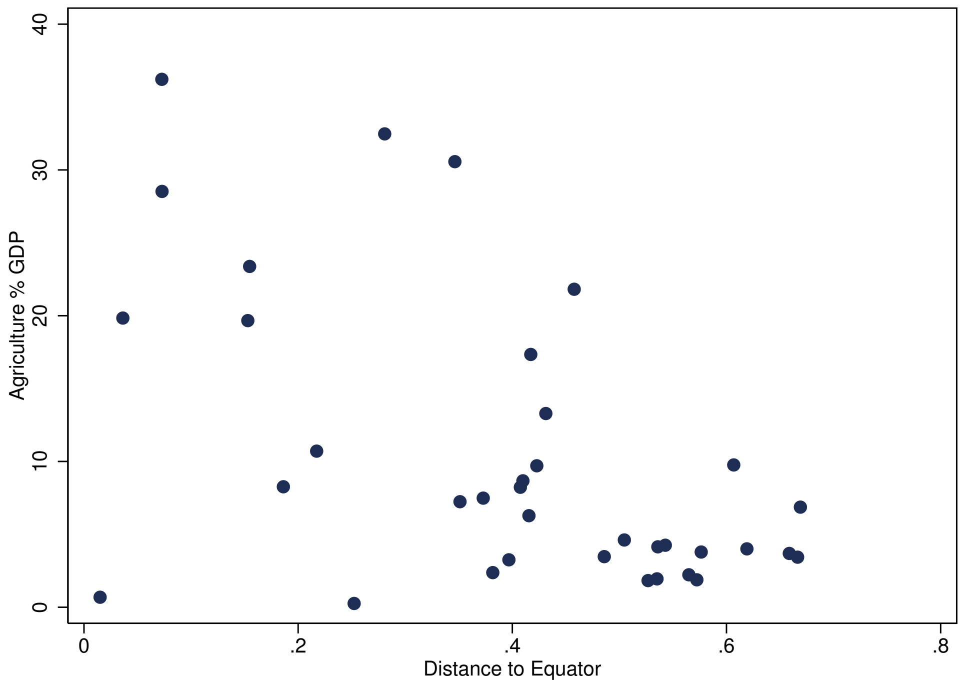


Figure 2.2 presents a scatter plot for the share of agriculture in GDP against the distance to the Equator for a sample of 38 countries. The share of agriculture in GDP is computed for the period 1960-2007. The distance from the equator is computed as the absolute value of the latitude in degrees divided by 90 to place it between 0 and 1.

FIGURE 2.2: Distance to the Equator and Agriculture share in GDP

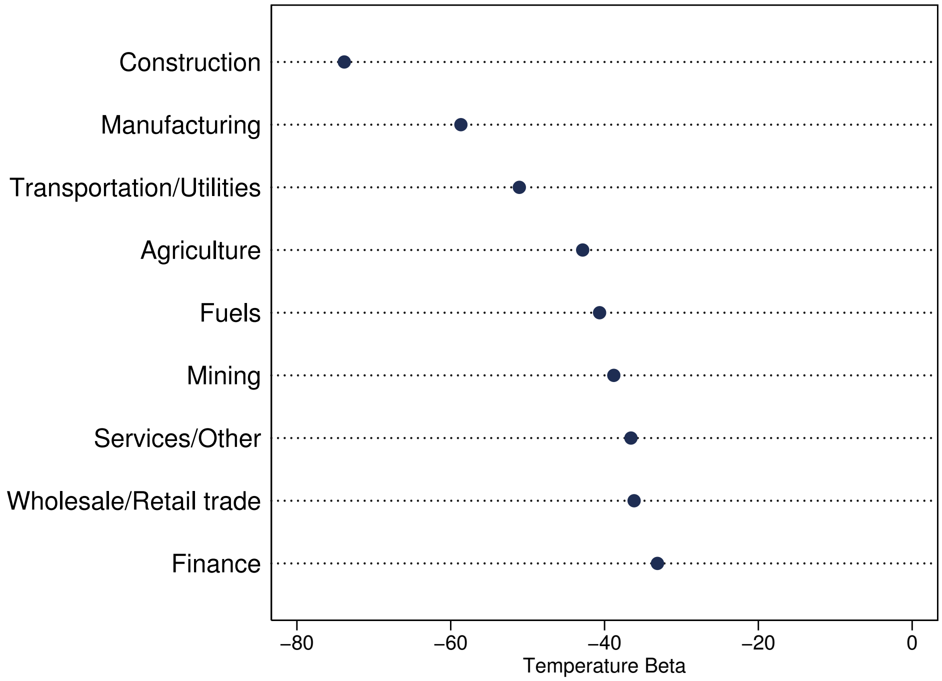


Figure 2.3 presents the temperature beta for nine U.S. industry portfolios. The industry groups are constructed using the two digit SIC codes. The temperature beta is obtained by regressing the market real return for each portfolio on the change in global temperature. The data on returns are annual, real, and expressed in percentage terms.

Figure 2.3: U.S. Industry Portfolios' Temperature Beta

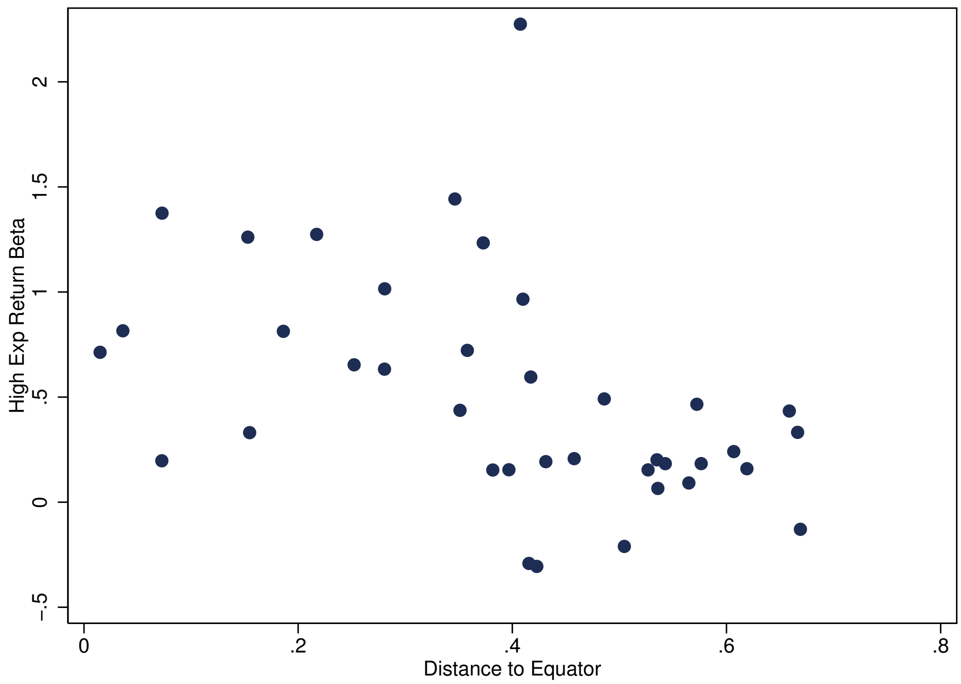
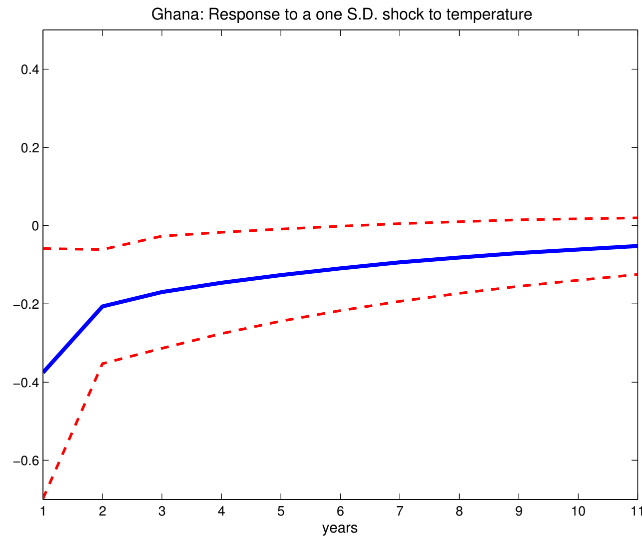


Figure 2.4 presents a scatter plot for the exposure to the return on the temperature sensitive portfolio against the distance to the Equator for 38 countries. The portfolio of temperature sensitive industries is composed of Construction, Manufacturing, Transportation and Utilities, and Agriculture. The 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 2.4: Distance to the Equator and Exposure to Temperature Sensitive Portfolio



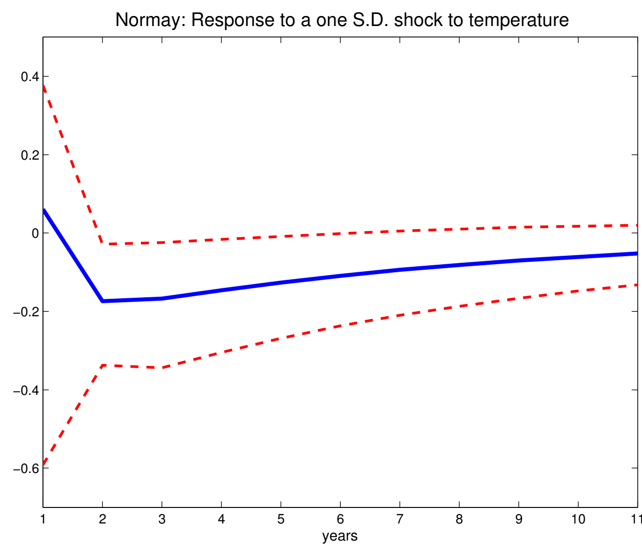


Figure 2.5 presents the response of GDP growth to a temperature shock in Ghana ($\ell = 0.07$ close to the Equator) and Norway ($\ell = 0.67$ far from the Equator). The impulse-response functions are computed using the dynamic model of GDP growth presented in Table 2.9.

FIGURE 2.5: Response of Growth to Temperature Shocks

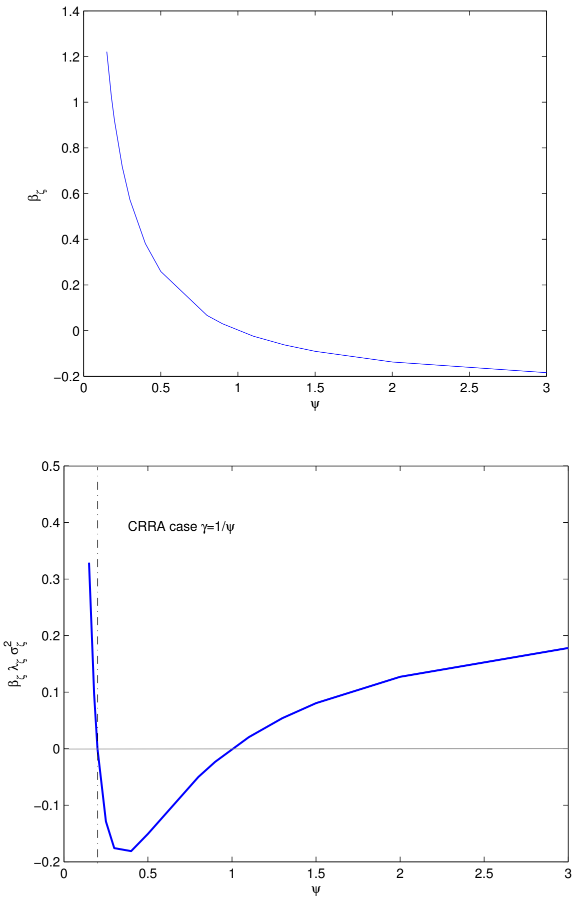


Figure 3.2 plots the temperature beta, and the contribution of temperature innovations to the risk premia at different values of the IES and setting the risk aversion parameter equal to 5. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ). The the compensation to temperature innovations, $\beta_\zeta \lambda_\zeta$, is expressed in annual percentage terms.

FIGURE 2.6: Temperature Risk at Different Values of the IES

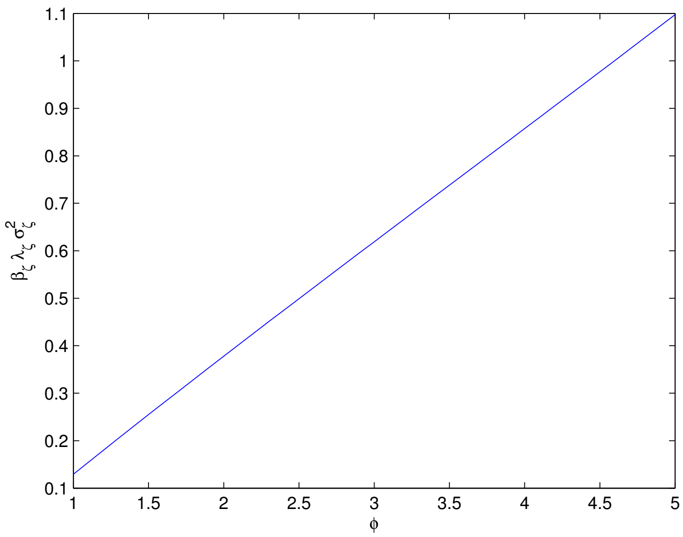


Figure 2.7 the contribution of temperature innovations to the risk premia at different values of dividend's exposure to long-run growth, ϕ. The compensation to temperature innovations, $\beta_{\zeta,m}\lambda_{\zeta}$, is expressed in annual percentage terms.

FIGURE 2.7: Temperature Risk and Dividend's Exposure to Long-Run Growth

3

Welfare Costs of Long-Run Temperature Shifts

3.1 Introduction

The accumulation of CO_2 and other Green House Gasses (GHG) in the atmosphere have led to a persistent rise in temperature over the last decades. If no policies to control emissions of CO_2 are put in place, the Fourth Assessment Report of the International Panel on Climate Change (IPCC (2007a)) warns that temperature might increase over the coming century as from 1.8 to 4.0°C. More recently, the IPCC (2012) projects that by the end of the 21st century there will be an increase in weather-related disasters, namely, the length and intensity of temperature extremes, the frequency of heavy precipitation and rainfalls associated with tropical cyclones, and local flooding. This paper evaluates the welfare implications of implementing climate policies to limit temperature risks and the economic impact of natural disasters using a long-run risks based general equilibrium model.

To understand the impact of climate change on the economy we propose a general equilibrium model that simultaneously models the world economy and global climate. Our model builds on Long-Run Risk (LRR) model of Bansal and Yaron (2004) which has been shown to jointly account for the observed consumption dynamics, the risk-free rate, the equity premium, and volatility puzzles among others. Our Long-Run Risks and Climate Integrated (LRR-C) model incorporates global temperature into the LRR model. We assume that global temperature and natural disasters link climate change and the economy. In particular, we assume that natural disasters have a negative impact on the economy by reducing growth of consumption. Also, the expected number of disasters at any point in time increases with global temperature. As in the LRR model we assume that the representative agent is characterized by recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty. These characteristics of our framework distinguish the LRR-C model from current benchmark Integrated Assessment Models (IAM) such us Nordhaus and Boyer (2003) DICE model.

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

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

Our estimates are similar in magnitude to those reported in Pindyck (2012). In his paper, using a general equilibrium model which incorporates uncertainty about the climate sensitivity, Pindyck (2012) also finds that society is willing to pay less than 2% of consumption now and forever to avoid an increase in temperature of 2 or 3°C. In contrast, our estimates are in between those reported in Stern (2006) and Nordhaus (2010). Stern (2006) argues that the overall costs associated with climate change are very large, they are equivalent to losing at least 5% of GDP each year, now and forever, and can be as high as 20% of GDP. Stern (2006) result would support the implementation of stringent CO_2 emissions abatement policies. On the other hand, Nordhaus (2010) finds that the welfare benefits of implementing any climate policy are below 0.4%. This result would support inaction if implementing policies to reduce CO_2 emissions are as high as 2% of GDP.

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

3.2 Long-Run Risks Temperature Model

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

3.2.1 Preferences

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

$$V_t = \left[(1-\delta)C_t^{\frac{1-\gamma}{\theta}} + \delta\Big(E_t\big[V_{t+1}^{1-\gamma}\big]\Big)^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}, \tag{3.1}$$

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

$$W_{t+1} = (W_t - C_t)R_{c,t+1}\ , \tag{3.2}$$

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

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

$$m_{t+1} = \theta \ln \delta - \frac{\theta}{\psi}\Delta c_{t+1} + (\theta - 1)r_{c,t+1} \tag{3.3}$$

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

$$M_{t+1\to t+j} \equiv \exp\left(\sum_{k=1}^{k=j} m_{t+k}\right) \tag{3.4}$$

3.2.2 Consumption Growth Dynamics

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

$$\Delta c_{t+1} = \mu + x_t + \sigma_t \eta_{t+1} + \varphi_c D_{t+1} \tag{3.5}$$

$$x_{t+1} = \rho x_t + \sigma_t \varphi_e e_{t+1} + \tau_w \sigma_\zeta \zeta_{t+1} + \varphi_x D_{t+1} \tag{3.6}$$

$$w_{t+1} = \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \tag{3.7}$$

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

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

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \xi_{i,t+1} - \lambda_t \mu_c, \tag{3.8}$$

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

$$\lambda_t = \ell_0 + \ell_1(w_t - \mu_w) \tag{3.9}$$

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

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

$$\sigma_t^2 = \sigma^2 + \nu(\sigma_t^2 - \sigma^2) + \sigma_v v_{t+1} \tag{3.10}$$

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

3.2.3 Temperature, Wealth and Risk Prices

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

$$E_t[\exp(m_{t+1} + r_{c,t+1})] = 1 \tag{3.11}$$

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

$$r_{c,t+1} = \kappa_0 + \kappa_1 z_{c,t+1} + \Delta c_{t+1} - z_{c,t}, \tag{3.12}$$

where $z_{c,t} = \log(P_t/C_t)$ is log price to consumption ratio (i.e., the valuation ratio corresponding to a claim that pays consumption) and κ's are log linearization constants.[1] In the Appendix we show that the solution for the price-consumption ratio is affine in the state variables

$$z_{c,t} = A_0 + A_x x_t + A_\sigma \sigma_t^2 + A_w w_t \tag{3.13}$$

where A_x, A_w, and A_σ must satisfy,

$$A_x = \frac{\left(1 - \frac{1}{\psi}\right) + \kappa_1 A_w \tau_x}{1 - \kappa_1 \rho} \tag{3.14}$$

$$A_\sigma = \frac{\frac{1}{2}\theta \left[\left(1 - \frac{1}{\psi}\right)^2 + (\kappa_1 A_x \varphi_e)^2 \right]}{1 - \kappa_1 \nu} \tag{3.15}$$

$$A_w = \frac{\ell_1 \Big[\Phi[(1-\gamma)\varphi_c + \theta \kappa_1 A_x \varphi_x] - 1 \Big]}{\theta(1 - \kappa_1 \rho_w)} \tag{3.16}$$

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

The impacts of expected growth and consumption volatility on the price to consumption ratio are determined by the preference configuration. Higher expected growth raises asset valuations and the price to consumption ratio only when the IES is larger than one. Similarly, a rise in consumption volatility lowers the price to

[1] These constants are equal,

$$\kappa_0 = \ln(1 + e^{z_c}) - \frac{e^{z_c}}{1 + e^{z_c}} z_c,$$

$$\kappa_1 = \frac{e^{z_c}}{1 + e^{z_c}},$$

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

consumption ratio when the IES is larger than one. Temperature impact on asset valuations is determined by A_w, which is different to zero only if natural disasters have an impact on the economy (i.e. $\varphi_c \neq 0$ and/or $\varphi_x \neq 0$). Figure 3.1 plots A_w for various values of the IES. If the IES is less than one then temperature will raise asset valuations, while IES larger than one is needed for temperature to lower the aggregate wealth to consumption ratio.

Replacing the solution for the return on wealth on the expression for the IMRS (3.3), the innovation to the pricing kernel conditional on the time t information at time $t+1$ equals,

$$m_{t+1} - E_t(m_{t+1}) = -\lambda_\eta \sigma_t \eta_{t+1} - \lambda_e \sigma_t e_{t+1} - \lambda_v \sigma_v v_{t+1} - \lambda_\zeta \sigma_\zeta \zeta_{t+1} - \lambda_D D_{t+1} \quad (3.17)$$

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

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

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

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

$$E_t(r_{c,t+1} - r_{f,t} + \frac{1}{2}V_t(r_{c,t+1})) = \beta_\eta \lambda_\eta \sigma_t^2 + \beta_x \lambda_e \sigma_t^2 + \beta_v \lambda_v \sigma_v^2 + \beta_\zeta \lambda_\zeta \sigma_\zeta^2 + \beta_D \lambda_D \lambda_t u_c^2 \quad (3.18)$$

where $r_{f,t}$ is the risk-free rate, β_η, β_x and β_v are the betas of the asset return with respect to the short-run risk, long-run risk, and volatility risk innovations, respectively. The exposure to temperature is determined by the beta of temperature innovations, β_ζ, and the beta of natural disasters β_D. As the market prices of risk, all asset betas are endogenous to the model and depend on preference and model dynamics parameters. The risk compensation from each source of risk is determined by the asset's β for that risk times the market price of that risk, λ.[2]

The risk compensation for temperature shocks, $\beta_\zeta \lambda_\zeta$, is positive only when agents have a preference for early resolution of uncertainty and the IES is larger than one. Figure 3.2 depicts the risk compensation from temperature innovations for different values of the IES and a risk aversion parameter equal to 10. As noted above, the market price of risk is zero when agents have CRRA preferences, i.e., $\psi = \frac{1}{\gamma}$. Moreover, the temperature beta is zero since long-run risks have no impact on asset valuations, A_x equals zero. For values of the IES between the CRRA case, $\psi = \frac{1}{\gamma}$, and 1, temperature shocks contribute negatively to the risk premia. In this case, the market price of temperature risk λ_ζ is negative, but the beta of temperature innovations $\beta_{c,\zeta}$ is positive since long-run growth decreases the value of assets, i.e., A_x is negative. For values of the IES larger than one, the beta of temperature innovations is negative because temperature innovations negatively impacts long-run growth, thereby, asset prices.

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

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

3.3 Economic Costs of Temperature Variation

3.3.1 Dollar Costs of Temperature Variation

To asses the economic costs of temperature we compute the difference in the market price of an asset that pays consumption as dividend and an asset that pays consumption after insuring it from all effects of temperature. The insured consumption claim C_t^*, $t = 1 \cdots \infty$, corresponds to the case where $\tau_w = 0$, $\varphi_c = 0$, and $\varphi_x = 0$; the resulting consumption process is insured in all states and dates against temperature fluctuations. Thus, the difference in the price of C^* and C is the premium, in dollar terms, that the society might be willing to pay to insure against the effects of temperature at current consumption state prices. The equilibrium prices are determined by the consumption dynamics C_t, $t = 1 \cdots \infty$, which include the temperature dynamics as described in equation (3.5).

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

$$P_t = \sum_{j=1}^{\infty} E_t[M_{t+1 \to t+j} C_{t+j}] \tag{3.19}$$

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

$$P_t^* = \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j} C_{t+j}^*] \tag{3.20}$$

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

$$\text{Dollar Costs } = \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j} C_{t+j}^*] - \sum_{j=1}^{\infty} E_t[M_{t+1\to t+j} C_{t+j}] \tag{3.21}$$

To compute the dollar costs we calculate the price-consumption ratio in both cases, with and without temperature risks, inside the model, and multiply its difference by the level of world consumption for the year 2009, i.e., we assume that initial aggregate consumption equals that of 2009.[3]

3.3.2 Welfare Costs of Temperature Variation

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

$$E\Big[U_0\Big((1+\Delta)C\Big)\Big] = E\Big[U_0(C^*)\Big] \tag{3.22}$$

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

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

$$\frac{U_t}{C_t} = (1-\delta)^{\frac{\psi}{\psi-1}} \frac{C_t}{W_t}^{\frac{\psi}{1-\psi}} \tag{3.23}$$

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

$$\frac{U_t}{C_t} = (1-\delta)^{\frac{\psi}{\psi-1}} (1 + Z_{c,t})^{\frac{\psi}{\psi-1}} \tag{3.24}$$

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

$$1 + \Delta = \frac{E\left[(1 + Z_c^*)^{\frac{\psi}{\psi-1}}\right]}{E\left[(1 + Z_c)^{\frac{\psi}{\psi-1}}\right]}. \tag{3.25}$$

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

3.4 Model Implications

3.4.1 Data Sources

We calibrate the model to capture world temperature dynamics, world growth, and world risk premium. The data on global temperature covering the period 1929–2009 are obtained from the Intergovernmental Panel on Climate Change Data Distribution Centre and comes from the Climate Research Unit (IPCC (2007b)). 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). [4] Annual temperature data corresponds to the average of monthly observations. Stock market data come from Morgan Stanley Capital International (MSCI) equity index. We consider the MSCI All Country World Index which measures equity returns across developed and emerging markets, 45 countries in total, to compute the world market equity return. We use the three-month T-bill rate to compute the risk-free rate. Real returns for all countries are obtained adjusting for U.S. inflation computed using the personal consumption expenditures (PCE) deflator from the National Income and Product Accounts (NIPA) tables. Data on world real GDP and real consumption come from the World Bank Development Indicators and cover the period 1960-2007.

Table 3.1 presents summary statistics for temperature dynamics, annual world GDP, consumption per capita growth, the world market real equity return, and the risk-free rate. The average global temperature is 14°, its volatility reaches 0.21 and its autoregressive coefficient equals 0.87. The average real GDP growth equals 1.91% while the average world consumption growth is about 1.84%. GDP growth volatility is around 1.4% and its autoregressive coefficient equals 0.44 while consumption growth volatility is nearly 1% and its autoregressive coefficient equals 0.41. The world market return is 6.83%, and the market return volatility equals 19.65%. The real risk-free rate averages 1.45% per annum, and its volatility is 2.03%, one-tenth

[4] To compute large-scale spatial means, each station is associated to a grid point of a $5^\circ \times 5^\circ$ 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.

of that of equity.

3.4.2 Calibration

As is standard in the literature, we assume that the decision interval of the agent is monthly. Table 3.2 presents the parameter configuration we use to calibrate the model, which we choose in order to match the joint dynamics of consumption growth and global temperature, the level of the risk-free rate, and the risk premium. Our baseline parametrization for preferences and the dynamics of consumption is very similar to that used in the long-run risks literature (e.g., Bansal et al. (2007b)). The subjective discount factor δ equals 0.999, the risk aversion parameter γ and the intertemporal elasticity of substitution ψ are equal to 10 and 1.5, respectively. Under this configuration, the agent has a preference for early resolution of uncertainty as in the long-run risk literature (e.g., Bansal and Yaron (2004)). As in Bansal et al. (2007b), 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.

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

To calibrate the the impact of temperature innovations on expected growth τ_w we aim to match the response world consumption growth to a temperature shock. Figure 3.3 depicts the impulse-response function obtained from a bi-variate VAR model of consumption growth and global temperature. In particular, it shows that a one standard deviation shock to temperature, about 0.2°C, reduces growth by 0.3% and its impact persists for up to twenty years. We choose a value of τ_w equal to

-0.0018 which implies a negative response of consumption growth to temperature as observed in the data. In the model, a temperature shock reduces temperature up to 0.2%, and has a non-negligible impact for up to twenty years, as in the data. More importantly, the response of consumption lies within the 95% confidence intervals of the empirical VAR model (see Figure 3.4). This calibration is also consistent with the empirical evidence in Bansal and Ochoa (2011) where we show that global temperature and shocks to global temperature have a negative impact on economic growth. Using a panel of 147 countries we show that a one standard deviation shock to temperature, about 0.2°C, lowers GDP growth by 0.24%. Moreover, our results indicate that temperature not only has a contemporaneous short-lived impact on economic growth, but its negative impacts tend to persist over time. Dell et al. (2009b) also show that an increase in temperature reduces GDP growth. Namely, a 1°C degree increase in temperature reduces growth by 1.1 percentage points for countries poor countries.

We set the compensated compound Poisson shock such that the probability of a natural disaster in a year is 1%, in other words, we assume the likelihood of one disaster every hundred years. We calibrate the sensitivity of the Poisson shock to temperature such that a 1°C increase in temperature doubles the probability of a natural disaster in a year. Therefore mean intensity of natural disasters ℓ_0 is set equal to 0.01/12 and its sensitivity to temperature ℓ_1 is equal to 0.01/12. We set the size of the Poisson jump μ_c such that the cost of a natural disasters equals 1.0% permanent reduction in consumption. As in Pindyck (2012) and Weitzman (2009), our calibration intends to explore the potential impact of tail events.

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

monthly simulated data aggregated to annual horizon.

3.4.3 Asset Pricing Implications

Our calibration of the model captures the bivariate dynamics of consumption and temperature. Table 3.3 presents the model implications for the consumption growth and temperature dynamics. In all of our specifications the first-order autocorrelation of consumption is around 0.43, which is very close to the data. Similarly, the model calibration matches the autocorrelation of temperature. As seen in Figures 3.3 and 3.4 the model also captures the negative and long-lasting response of consumption growth to temperature. The negative correlation between growth rates and temperature arises from the fact that temperature shocks impact negatively the expected growth rate of consumption, x_t. Even in the presence of natural disasters, shutting down this channel prevents the model from accounting for this feature of the data.

In our framework, where agents are not indifferent about the timing of uncertainty resolution, temperature risks are priced and contribute to the risk premium on the consumption claim as well as to the equity risk premium. Using the expression for the consumption risk premium, equation (3.18), we find that in the category 1 model the risk compensation for temperature accounts for about 1.1 basis points of the total risk premium on the consumption claim of 2.04%. Including the possibility of natural disasters, in the category 2 model, the temperature impact on long-run growth accounts for 1.1 basis points of the risk premium while natural disasters account for only 0.1 basis points, therefore temperature accounts for 1.2 basis points of the risk premium. Therefore, the risk premium on the consumption claim in category 2 model is slightly larger than category 1, but the difference is very small. The figures on the risk premium for the consumption asset are very close to the results of Lustig et al. (2009), who find that the consumption risk premium is 2.2% per year, and the discount rate on the consumption claim is 3.49% per year.

The model also matches the moments of the risk-free rate, and the market return (see Table 3.3). The risk-free rate, in category 1 and category 2 models is about 1.1%, and the volatility of the risk-free is about 1.14%; for both models the levels and volatility match the data well. On the other hand, the return on the equity claim is higher and more volatile. For category 2 the expected market return is 7.07%, with a volatility equal to 18.90%, giving rise to an equity premium of about 6%; the premium is slightly higher in the category 2 model. Moreover, the magnitude and volatility of equity returns are six times higher than the magnitude and volatility of the return on consumption. As in the LRR model of Bansal and Yaron (2004) the risks associated with the long-run growth are critical for explaining the risk premium in the economy, as it not only accounts for a significant portion of the premium but also magnifies the contribution of the volatility risk.

3.4.4 Dollar Costs of Temperature Variation

The second panel of Table 3.4 presents the price-consumption ratio and the return on a asset that delivers the consumption stream, C^*, as its dividends. In all cases, as expected, the asset which removes the effects of temperature variation has a higher price-consumption ratio as it is insured against temperature related risks. The first panel of the table presents the difference in the price of an asset paying consumption with and without the effects of temperature in US$ dollars of 2009, which represent the losses in US$ dollars from temperature variation as priced by financial markets.[5] The dollar losses from temperature in our models range from 1.43 US$ trillion to 3.18 US$ trillion dollars, which imply a loss from 2.46% to 5.47% of GDP.

The key driver of these dollar costs is the change in the riskiness of the consumption claim. For example, in the category 2 model, the expected return on the

[5] We use World consumption for the year 2009 to compute the price of these assets as explained in section 3.3.

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

3.4.5 Welfare Costs of Temperature Variation

In the spirit of Lucas (1987) costs of business cycles, we start by asking how much individuals would be willing to give up, in terms of percentage annual consumption, to live in a world exempt from the effects of temperature. The first row of Table 3.5 presents the welfare costs of temperature variation for the two alternative models we entertain. In the category 1 model, when only innovations to temperature have an impact on expected growth, welfare costs are equal to 0.78%. Incorporating temperature-triggered natural disasters raises the the welfare costs marginally to 0.81%. Natural disasters have only a small impact relative to temperature shocks because the size of the disasters are quite small and more importantly, they are transient and do not affect long-run growth. When φ_x is positive, natural disasters lower long-run growth and in this case their impact on welfare can be quite significant. However, for the most part, evidence indicates that natural disasters have only a short run impact on growth (see e.g Rasmussen (2004)), and for this reason we set $\varphi_x = 0$

To interpret these magnitudes for our two models it is useful to recall that welfare costs computations of eliminating business cycles reported in Lucas (1987) and much of the literature (see Barlevy (2004) for a review) are quite small, well less than 1% of GDP; hence our magnitudes of welfare-costs for temperature stabilization are in the upper bound to those typically reported for business cycles. Furthermore, in line with our findings, Pindyck (2012) shows that, in a model in which agents have uncertainty about temperature dynamics and its impact on growth, welfare costs are below 2% for parameter values consistent with scientific studies assembled by the International Panel on Climate Change (IPCC).

3.4.6 Interpreting Temperature Related Costs

Two key ingredients in the Bansal and Yaron (2004) LRR model explain the sizeable dollar and welfare costs associated with temperature fluctuations; (i) the recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty, and (ii) a standard long-frequency fluctuation for consumption growth with a persistent expected growth component. Table 3.6 presents the simulations of our specifications first assuming that preferences are described by a CRRA utility function, i.e. $\gamma = \frac{1}{\psi}$ but otherwise maintain the LRR specification (CRRA-LRR) for growth rates. We also simulate the model keeping the original assumption of recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty but letting consumption be *iid*, thus temperature innovations and natural disasters impact its high frequency component (EZW-hf). In all exercises we keep the relevant parameter values same as our calibration, and in the EZW-hf we calibrate the standard deviation of the high frequency innovation such that it equals the monthly consumption volatility for our category 1 model.

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

3.5 Conclusions

This paper makes a contribution towards understanding the impact of temperature fluctuations on the economy and financial markets. We present a temperature related long-run risks equilibrium model, which simultaneously matches the observed temperature and growth dynamics, and key dimensions of the financial markets data. We use this model to evaluate the role of temperature in determining asset prices, and to compute the utility-based welfare costs as well as the dollar costs of insuring against temperature fluctuations. Our model implies that if temperature were to rise it would lower long-run growth, raise risk-premiums, and adversely affect asset prices — the magnitude of these negative effects increases with temperature, suggesting that global warming presents a significant risk. We find that the temperature related utility-costs are about 0.78% of consumption, and the total dollar costs of completely insuring against temperature variation are about 2.46% of World GDP. We show that the same features, long-run risks and recursive-preferences, that account for the risk-free rate and the equity premium puzzles (among others) also imply that temperature-related costs are important and that temperature-risks carry a positive risk premium. In future work an important ingredient, as appropriately emphasized by Weitzman (2009), is to incorporate temperature-related model uncertainty in the analysis.

3.6 Tables and Figures

Table 3.1: 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)

Notes: Table 3.1 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 3.2: Configuration of Model Parameters

Preferences	δ	γ	ψ			
	0.999	10	1.5			

Consumption	μ	ρ	φ_e	σ	ν	σ_w
	0.0015	0.975	0.036	0.0006	0.999	0.0000028

Dividends	μ_d	ϕ	π	φ_u		
	0.0015	2.5	1.75	5.96		

Temperature	μ_w	ρ_w	τ_x	σ_ζ		
	14.6	0.985	0.0	0.025		

Category 1	τ_w	φ_c	φ_x			
	-0.0018	0	0			

Category 2	τ_w	φ_c	φ_x	ℓ_0	ℓ_1	μ_c
	-0.0018	-1.0	0	1/(1200)	1/(1200)	0.01

Notes: Table 3.2 reports configuration of investors' preferences and time-series parameters that describe the dynamics of consumption, dividend growth rates, and temperature. The model is calibrated on a monthly basis. The state of the economy is described by,

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

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

Table 3.3: Model Implied Dynamics of Growth Rates and Returns

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

Notes: Table 3.3 reports moments of aggregate consumption (c_t), temperature (w_t) growth rates, the return on the consumption claim (R_c), the return on the market dividend claim (R_m), and the risk-free rate (R_f). Data statistics along with standard deviations (in parentheses) are reported in the first column. The data are real, sampled on an annual frequency, and are expressed in percentage terms. The next two columns present model based statistics based on $12 \times 20,000$ monthly data aggregated to annual observations.

Table 3.4: Model-Based Dollar Costs of Global Warming

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

Notes: Table 3.4 reports the cost in dollar terms of a reduction in consumption due to temperature risks. The cost of a reduction in consumption is computed as the difference between the price of a consumption-paying asset with and without the effects of temperature. The price-consumption ratio and return of the consumption claim with temperature risks are denoted P/C and R_c, respectively. The price-consumption ratio and return of the consumption claim without temperature risks in the same economy are denoted P^*/C^* and R_{c*}, respectively. All reported figures are computed based on $12 \times 20,000$ monthly data aggregated to annual horizon. Returns are expressed in percentage terms.

Table 3.5: Model-Based Welfare Costs of Global Warming

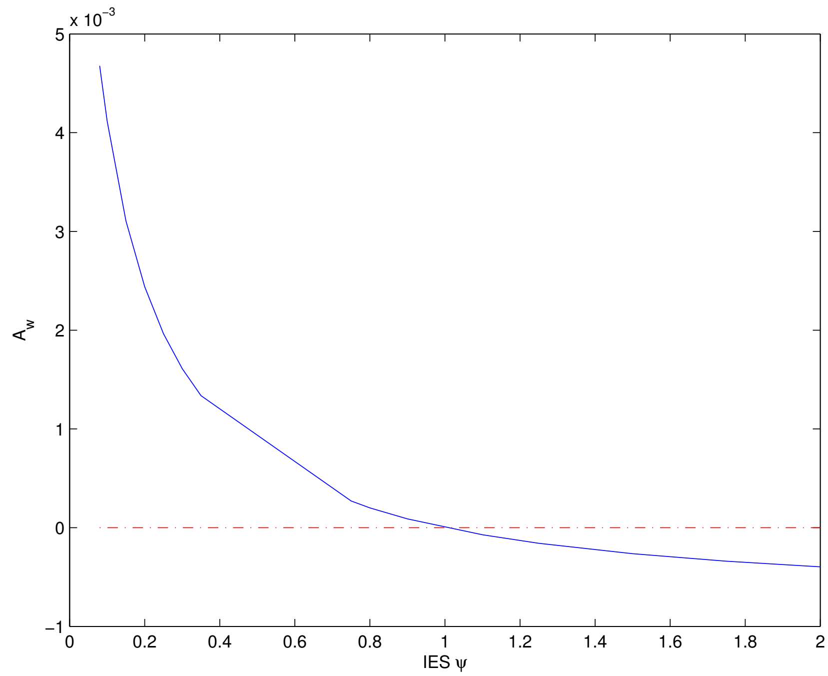
	Model	
	Category 1	Category 2
Welfare Costs of Stabilization	0.78	0.81
Temperature Growth Shock		0.79
Natural Disasters		0.02
Economy with temperature risks		
Risk-premium on consumption claim	2.040	2.041
Price-consumption ratio	74.984	74.978
Economy w/o temperature risks		
Risk-premium on consumption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

Notes: Table 3.5 reports welfare costs of setting temperature effects to zero and the return as well as the price-consumption ratio of a consumption claim in an economy with and without the risks of temperature. The welfare costs of stabilization represents the fraction of consumption that the representative agent would be willing to give up to avoid the negative effects of global warming. All reported figures are computed based on $12 \times 20,000$ monthly data aggregated to annual horizon. Returns are expressed in percentage terms.

Table 3.6: Role of LRR and Recursive Preferences

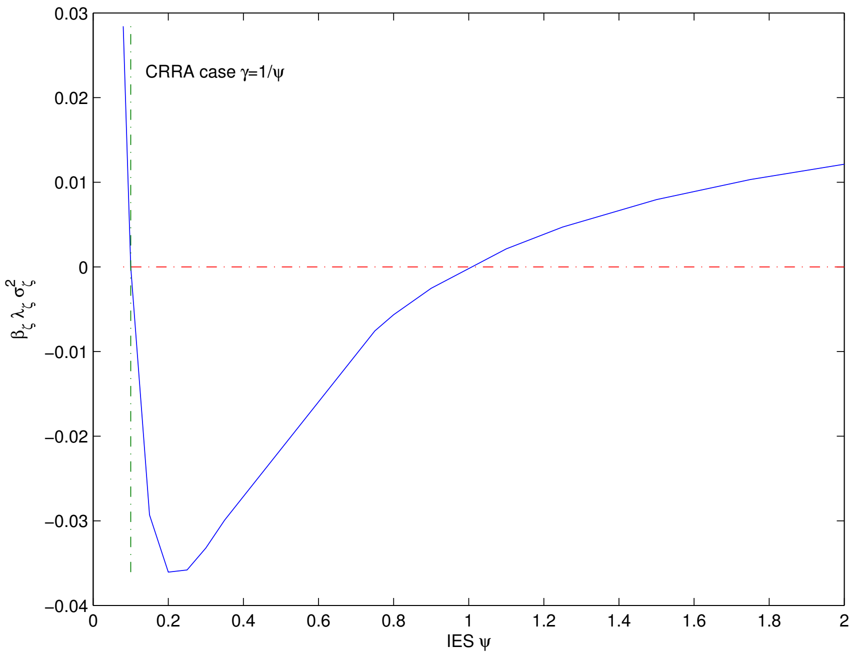
	CRRA–LRR		**EZW–hf**	
	Category 1	Category 2	Category 1	Category 2
Welfare Costs	0.04%	0.04%	0.001%	0.07%
$E[R_f]$	16.756	16.751	1.802	1.801
$\sigma[R_f]$	16.079	16.078	0.000	0.000
$E[R_c - R_f]$	0.676	0.676	0.787	0.787
$E[R_m - R_f]$	1.302	1.303	1.412	1.415

Table 3.6 presents model based welfare costs, the risk-free rate and risk premia assuming (i) CRRA–LRR, that preferences are described by a CRRA utility function, i.e. $\gamma = \frac{1}{\psi}$ but otherwise maintain the LRR specification, and (ii) EZW-hf recursive preferences of Epstein and Zin (1989) and Weil (1990) with a preference for early resolution of uncertainty and letting consumption be *iid*, thus temperature innovations and natural disasters impact its high frequency component. R_c is the return on the consumption claim, R_f the risk-free rate, and R_m is the return on the market dividend claim. All reported figures are computed based on $12 \times 20,000$ monthly data aggregated to annual horizon.



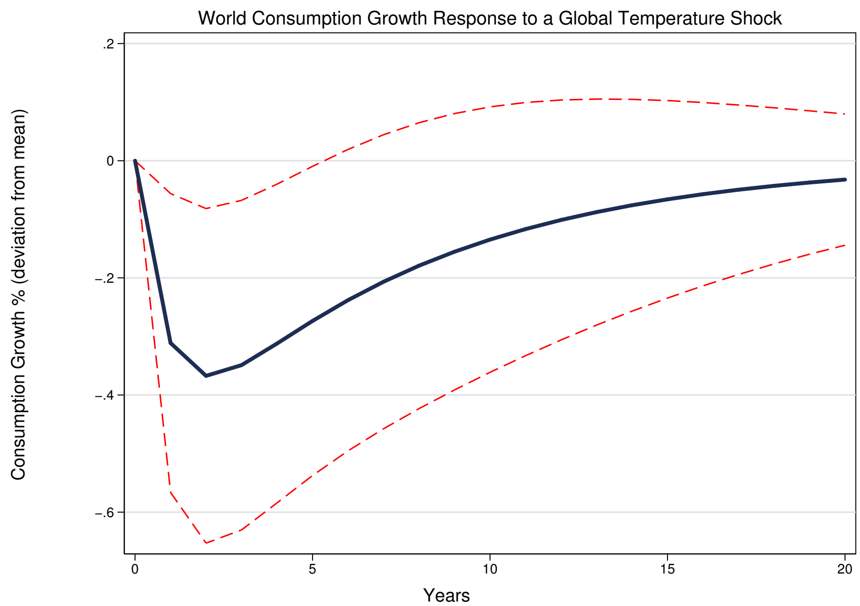
Notes: Figure 3.1 plots the elasticity of the price-consumption ratio to temperature, A_w, at different values of the IES and setting the risk aversion parameter equal to 10. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ).

FIGURE 3.1: Temperature Impact on Asset Prices for IES



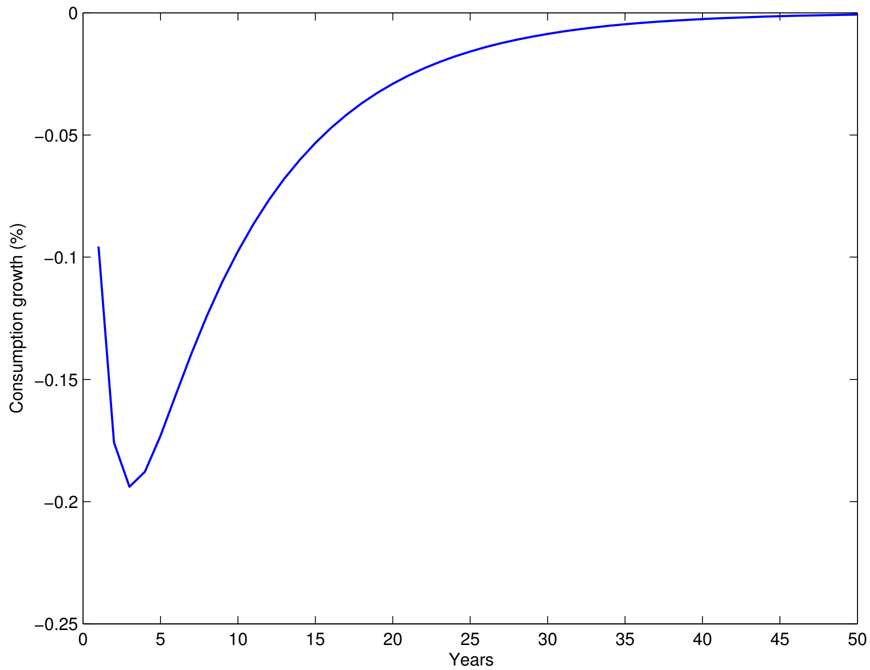
Notes: Figure 3.2 plots the temperature beta, and the contribution of temperature innovations to the risk premia at different values of the IES and setting the risk aversion parameter equal to 10. The CRRA case refers to the situation when the risk aversion parameter (γ) equals the inverse of the IES (ψ). The the compensation to temperature innovations, $\beta_\zeta \lambda_\zeta$, is expressed in annual percentage terms.

FIGURE 3.2: Temperature Risk at Different Values of the IES



Notes: Figure 3.3 presents the impulse-response function from a bivariate VAR of world consumption growth and global temperature. The figure depicts the response of consumption growth to a one standard deviation shock to temperature (solid line) along with 95% confidence bands (dashed lines). The data on world consumption is real and covers the period 1960-2007.

FIGURE 3.3: Global Growth and Temperature



Notes: Figure 3.4 presents the response of consumption growth to a one standard deviation shock to temperature implies by a bivariate VAR model. The VAR is estimated using $12 \times 20,000$ monthly data aggregated to annual observations on consumption growth and temperature.

Figure 3.4: Model Implications for Growth and Temperature

Appendix A

Appendix to Chapter 1

A.1 Solving the Stochastic Discount Factor

To solve for the stochastic discount factor note that the return on wealth satisfies the standard asset pricing restriction condition,

$$1 = \mathbb{E}_t \left(M_{t,t+1} R_{c,t+1} \right) \tag{A.1}$$

which can be written as,

$$1 = \mathbb{E}_t \left(\beta^{\frac{1-\gamma}{1-1/\psi}} \left(\frac{C_{t+1}}{C_t} \right)^{1-\gamma} \left(\frac{Z_{t+1}}{Z_t - 1} \right)^{\frac{1-\gamma}{1-1/\psi}} \right) \tag{A.2}$$

The state variables, a_t and σ_t, in the model follow a Markov chain; therefore the wealth-consumption ratio is a time-invariant function of the state variables $Z_t = Z(a_t, \sigma_t)$. Replacing consumption growth using equation (1.9) and making explicit the dependence of the wealth consumption ratio on the state variables we have that

$Z(a_t, \sigma_t)$ must solves the following system of equations,

$$1 = \mathbb{E}_{a_t,\sigma_t}\left(\beta^{\frac{1-\gamma}{1-1/\psi}} \exp\left((1-\gamma)(\mu + \phi(a_t - \mu) + \eta_{t+1})\right)\left(\frac{Z(a_{t+1}, \sigma_{t+1})}{Z(a_t, \sigma_t) - 1}\right)^{\frac{1-\gamma}{1-1/\psi}}\right) \tag{A.3}$$

To solve for the wealth-consumption ratio, I solve the following system of equations,

$$\begin{aligned}(Z(a_t, \sigma_t) - 1)^{\frac{1-\gamma}{1-1/\psi}} &= \beta^{\frac{1-\gamma}{1-1/\psi}} \exp\left((1-\gamma)(\mu + \phi(a_t - \mu)) + (1-\gamma)^2\sigma/2\right) \\ &\times \mathbb{E}_{a_t,\sigma_t}\left(Z(a_{t+1}, \sigma_{t+1})^{\frac{1-\gamma}{1-1/\psi}}\right)\end{aligned}$$

A.2 Solving the Dynamic Problem of the Firm

Equation (1.11) presents the recursive problem of the firm which is,

$$\nu(\mathbf{s}_t) = \max_{n_t, h_t} A_t(n_t^e h_t)^\alpha - w(h_t, n_t^e) - \sum_j C^j(n_t^j, n_{t-1}^j)\mathbf{1}_{n_t^j \neq n_{t-1}^j} + \mathbb{E}_t\left(M_{t,t+1}\nu(\mathbf{s}_{t+1})\right) \tag{A.4}$$

where I suppressed any firm specific subscript to save notation.

To obtain the stationary representation of the firm's problem, let

$$\tilde{n}_t = \frac{n_t}{A_t^{1/(1-\alpha)}}$$

and let

$$\frac{C^j(n_t^j, n_{t-1}^j)}{A_t^{1/(1-\alpha)}} = C^j\left(\tilde{n}_t^j, \left(\frac{A_t}{A_{t-1}}\right)^{-1/(1-\alpha)} \tilde{n}_{t-1}^j\right) \tag{A.5}$$

then, the stationary representation of the recursive problem is given by,

$$\tilde{\nu}(n_{t-1}, a_t, \sigma_t) = \max_{\tilde{n}_t} ((\lambda\omega + 1 - \omega)n_t h_t^*)^\alpha - (w_0 + w_1 h_t^{*\phi})(\theta\omega + 1 - \omega)n_t$$

$$- C^1 \left(\omega n_t, \left(\frac{A_t}{A_{t-1}}\right)^{-1/(1-\alpha)} \omega n_{t-1}\right) - C^2 \left((1-\omega)n_t, \left(\frac{A_t}{A_{t-1}}\right)^{-1/(1-\alpha)} (1-\omega)n_{t-1}\right)$$

$$+ \mathbb{E}_t \left(M_{t,t+1} \left(\frac{A_{t+1}}{A_t}\right)^{1/(1-\alpha)} \tilde{\nu}(n_t, a_{t+1}, \sigma_{t+1})\right)$$

where the optimal hours satisfy,

$$h_t^* = \left(\frac{\alpha A_t((\lambda\omega + 1 - \omega)n_t)^{\alpha-1}}{w_1 \zeta}\right)^{\frac{1}{\zeta-\alpha}} \tag{A.6}$$

and $\tilde{\nu}(n_{t-1}, a_t, \sigma_t)$ is equal to $\frac{\nu(n_{t-1}, A_t, a_t, \sigma_t)}{A_t^{1/(1-\alpha)}}$.

I solve the stationary representation of the model using value function iteration. To accelerate convergence, I use the multi-grid algorithm of Chow and Tsitsiklis and policy function iteration as described in Rust. The final number of grids for optimal employment-productivity ratio $\tilde{n}_t$ is 800, and I use nine states to approximate the dynamics of a_t.

Appendix B

Appendix to Chapter 2

B.1 Analytical Solution of Asset Prices

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

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

$$x_{t+1} = \rho x_t + \tau_w \sigma_\zeta \zeta_{t+1} + \sigma\varphi_e e_{t+1} \tag{B.2}$$

$$w_{t+1} = \mu_w + \rho_w(w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \tag{B.3}$$

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

B.1.1 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 (2.9) and the log-linear approximation of the return on the consumption claim asset (3.12) we have,

$$E_t[\exp(m_{t+1}+r_{c,t+1})] = E_t\left[\exp\left(\theta\ln\delta + \theta\left(1-\frac{1}{\psi}\right)\Delta c_{t+1} + \theta\kappa_0 + \theta\kappa_1 z_{c,t+1} - \theta z_{c,t}\right)\right] \tag{B.4}$$

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 (C.6) 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,

$$A_x = \frac{1-\frac{1}{\psi}}{1-\kappa_1\rho} \tag{B.5}$$

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,

$$\kappa_0 = \ln\left(1+e^{z_c}\right) - \kappa_1 z_c \tag{B.6}$$

$$\kappa_1 = \frac{e^{z_c}}{1+e^{z_c}} \tag{B.7}$$

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 (C.10) and (C.11) we have:

$$\kappa_0 = -\kappa_1 \ln \kappa_1 - (1-\kappa_1)\ln(1-\kappa_1) \tag{B.8}$$

$$\kappa_0 - (1-\kappa_1)A_0 = -\ln \kappa_1 \tag{B.9}$$

therefore, using (C.13) we can eliminate κ_0 and A_0 from (C.10). 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 (C.12) and (C.13), 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,

$$r_{c,t+1} = \mu_c + \kappa_0 - A_0(1-\kappa_1) + \frac{1}{\psi}x_t + \sigma\eta_{t+1} + \kappa_1 A_x \varphi_e \sigma e_{t+1} + A_x \tau_w \kappa_1 \sigma_\zeta \zeta_{t+1} \tag{B.10}$$

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.

B.1.2 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,

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

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 $r_{f,t}$:

$$r_{f,t} = r_f + A_{f,x} x_t \tag{B.12}$$

with,

$$r_f = -m_0 - \frac{1}{2}(\lambda_n^2 + \lambda_e^2)\sigma^2 - \frac{1}{2}\lambda_\zeta^2 \sigma_\zeta^2 \tag{B.13}$$

$$A_{f,x} = -m_x \tag{B.14}$$

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

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

where the β's are equal to,

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

B.1.3 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,

$$\Delta d_{t+1} = \mu_d + \phi x_t + \pi\sigma\eta_{t+1} + \varphi_u \sigma u_{t+1} \tag{B.15}$$

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,

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

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,

$$A_{x,m} = \frac{\phi - \frac{1}{\psi}}{1 - \kappa_{1,m}\rho} \tag{B.16}$$

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.2 Countries Grouped by Distance to the Equator

Group 1	Niger	India*	New Zealand*
Angola	Nigeria*	Israel	Portugal*
Barbados	Panama	Jamaica	Romania
Belize	Papua n.guinea	Jordan*	Spain*
Benin	Peru	Kuwait	Switzerland*
Bolivia	Philippines*	Lesotho	Syria
Burkina Faso	Rwanda	Madagascar	Tunisia
Burundi	Senegal	Mauritius	Turkey*
Cameroon	Seychelles	Mozambique	United States*
Cape Verde Islands	Sierra Leone	Nepal	Uruguay
Central African Rep.	Singapore*	Oman	**Group 4**
Chad	Solomon is.	Pakistan*	Belgium*
Colombia	Somalia	Paraguay	Denmark*
Comoros	Sri Lanka	Puerto Rico	Finland*
Congo	St. Kitts	Qatar	Iceland
Costa Rica	St. Lucia	Saudi Arabia	Ireland*
Djibouti	St. Vincent	South Africa	Luxembourg
Dominica	Sudan	Swaziland	Netherlands*
Ecuador	Suriname	Taiwan*	Norway*
El Salvador	Tanzania	Tonga	Poland
Ethiopia	Thailand*	United Arab Em.	Sweden*
Fiji	Togo	Vietnam	U.K.*
Gabon	Trinidad& Tobago	**Group 3**	
Gambia	Uganda	Algeria	
Ghana	Vanuatu	Argentina*	
Grenada	Venezuela	Austria*	
Guatemala	Western Samoa	Bulgaria	
Guinea	Zaire	Canada*	
Guinea-Bissau	Zambia	Chile *	
Guyana	Zimbabwe	Cyprus	
Honduras	**Group 2**	France*	
Indonesia*	Australia*	Germany*	
Ivory Coast	Bahamas	Greece*	
Kenya	Bahrain	Hungary	
Laos	Bangladesh	Iran	
Liberia	Bhutan	Iraq	
Malawi	Botswana	Italy*	
Malaysia*	Brazil*	Japan*	
Mali	China	Korea*	
Mauritania	Dominican rep.	Lebanon	
Mexico*	Egypt	Malta	
Namibia	Haiti	Mongolia	
Nicaragua	Hong Kong*	Morocco	

* denotes countries with asset market data.

Appendix C

Appendix to Chapter 3

C.1 Model solution

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

$$\Delta c_{t+1} = \mu_c + x_t + \sigma_t \eta_{t+1} + \varphi_c D_{t+1} \tag{C.1}$$

$$x_{t+1} = \rho x_t + \sigma_t \varphi_e e_{t+1} + \tau_w \sigma_\zeta \zeta_{t+1} + \varphi_x D_{t+1} \tag{C.2}$$

$$w_{t+1} = \mu_w + \rho_w (w_t - \mu_w) + \tau_x x_t + \sigma_\zeta \zeta_{t+1} \tag{C.3}$$

$$\sigma^2_{t+1} = \sigma^2 + \nu(\sigma^2_t - \sigma^2) + \sigma_v v_{t+1} \tag{C.4}$$

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

$$D_{t+1} = \sum_{i=1}^{N_{t+1}} \xi_{i,t+1} - \lambda_t \mu_c \tag{C.5}$$

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

C.1.1 Solution for the Consumption Claim

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

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

Combining the expressions for the pricing kernel (3.3) and the log-linear approximation of the return on the consumption claim asset (3.12) we have,

$$E_t[\exp(m_{t+1}+r_{c,t+1})] = E_t\left[\exp\left(\theta\ln\delta + \theta\left(1-\frac{1}{\psi}\right)\Delta c_{t+1} + \theta\kappa_0 + \theta\kappa_1 z_{c,t+1} - \theta z_{c,t}\right)\right] \tag{C.6}$$

Assuming that the solution for the price-consumption ratio is affine in the state variables $z_{c,t} = A_0 + A_x x_t + A_\sigma\sigma_t^2 + A_w w_t$, and replacing Δc_{t+1} we have that,

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

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

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

where we define $\Phi(\tau) = \exp(\tau\mu_c) - \tau\mu_c$. Note that to go from the first to the second line we use the definition of the moment generating function of a Poisson process, $E_t[\exp(\tau N_{t+1})] = \exp[\lambda_t(e^\tau - 1)]$, and the last expressions results from replacing the definition of λ_t. Using these last results, evaluating the expectation (C.6) and taking logs of both sides results in the following equation:

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

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

$$A_x = \frac{\left(1-\frac{1}{\psi}\right)+\kappa_1 A_w \tau_x}{1-\kappa_1\rho} \tag{C.7}$$

$$A_\sigma = \frac{\frac{1}{2}\theta\left[\left(1-\frac{1}{\psi}\right)^2+(\kappa_1 A_x \varphi_e)^2\right]}{1-\kappa_1\nu} \tag{C.8}$$

$$A_w = \frac{\ell_1\left[\Phi((1-\gamma)\varphi_c+\theta\kappa_1 A_x\varphi_x)-1\right]}{\theta(1-\kappa_1\rho_w)} \tag{C.9}$$

and A_0 satisfies,

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

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

$$\kappa_0 = \ln\left(1+e^{z_c}\right)-\kappa_1 z_c \tag{C.10}$$

$$\kappa_1 = \frac{e^{z_c}}{1+e^{z_c}} \tag{C.11}$$

where $z_c = E(z_{c,t}) = A_0 + A_\sigma\sigma^2 + A_w w$. As can be seen from these expressions, the log-liner coefficients depend on the values of A_0, A_x, A_σ and A_w which also depend on these coefficients. Therefore, these must be solved jointly with the loadings A_0, A_x, A_σ and A_w, since they are endogenous to the model. Manipulating equations (C.10) and (C.11) we have:

$$\kappa_0 = -\kappa_1\ln\kappa_1-(1-\kappa_1)\ln(1-\kappa_1) \tag{C.12}$$

$$\kappa_0-(1-\kappa_1)A_0 = -\ln\kappa_1+(1-\kappa_1)A_\sigma\sigma^2+(1-\kappa_1)A_w w \tag{C.13}$$

therefore, using (C.13) we can eliminate κ_0 and A_0 from (C.10) leading to the following expression that κ_1 must satisfy,

$$\begin{aligned}\ln\kappa_1 &= \ln\delta + \left(1-\frac{1}{\psi}\right)\mu + (1-\kappa_1)A_\sigma\sigma^2 + (1-\kappa_1)A_w w + \kappa_1\sigma^2(1-\nu)A_\sigma \\ &+\kappa_1 A_w(1-\rho_w)\mu_w + \frac{\theta}{2}(\kappa_1 A_\sigma)^2\sigma_v^2 + \frac{(\ell_0-\ell_1\mu_w)[\Phi((1-\gamma)\varphi_c+\theta\kappa_1 A_x\varphi_x)-1]}{\theta} \\ &+\frac{\theta}{2}(\kappa_1 A_x\tau_w + \kappa_1 A_w)^2\sigma_\zeta^2 \qquad (C.14)\end{aligned}$$

Given a starting value for κ_1 we solve for A_x, A_σ and A_w, which we use to iterate on κ_1 in (C.14) until it converges. Finally, using the solution for κ_1 and A_σ and A_w we can recover κ_0 and A_0 from equations (C.12) and (C.13), respectively.

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

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

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

C.1.2 Solution for the Pricing Kernel and the Risk-Free Rate

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

$$m_{t+1} = m_0 + m_x x_t + m_\sigma\sigma_t^2 + m_w w_t - \lambda_\eta\sigma_t\eta_{t+1} - \lambda_e\sigma_t e_{t+1} - \lambda_v\sigma_v v_{t+1} - \lambda_\zeta\sigma_\zeta\zeta_{t+1} - \lambda_D D_{t+1} \qquad (C.15)$$

with,

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

and

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

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

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

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

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

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

$$r_{f,t} = r_f + A_{f,x}x_t + A_{f,\sigma}\sigma_t^2 + A_{f,w}w_t \tag{C.16}$$

with,

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

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

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

where the β's are equal to,

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

C.1.3 Solution for the Consumption Paying Asset exempt from Global Warming Effects

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

$$\Delta c^*_{t+1} = \mu + x^*_t + \sigma_t \eta_{t+1} \tag{C.17}$$

$$x^*_{t+1} = x_{t+1} - \tau_w \sigma_\zeta \zeta_{t+1} - \varphi_x D_{t+1} \tag{C.18}$$

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

$$r_{c*,t+1} = \kappa^*_0 + \kappa^*_1 z_{c*,t+1} + \Delta c^*_{t+1} - z_{c*,t}, \tag{C.19}$$

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

$$E_t[\exp(m_{t+1} + r_{c*,t+1})] = 1 \tag{C.20}$$

To solve for the return we conjecture that the solution to the price-dividend ratio is $z_{c*,t} = A^*_0 + A^*_x x_t + A^*_\sigma \sigma^2_t + A^*_w w_t + A^*_\zeta \sigma_\zeta \zeta_t + A^*_D D_t$. Replacing our conjecture into the Euler equation as well as the expression for the pricing kernel (C.15) and evaluating the expectations, we obtain the following expressions for the loadings on the price-consumption ratio $z_{c*,t}$:

$$A^*_x = \frac{\left(1 - \frac{1}{\psi}\right) + \kappa^*_1 A^*_w \tau_x}{1 - \kappa^*_1 \rho} \tag{C.21}$$

$$A^*_\sigma = \frac{m_\sigma + \frac{1}{2}\left[(\kappa^*_1 A^*_x \varphi_e - \lambda_e)^2 + (1 - \lambda_\eta)^2\right]}{1 - \kappa^*_1 \nu} \tag{C.22}$$

$$A^*_w = \frac{m_w + \ell_1 \left[\Phi(\kappa^*_1 \varphi_x (1 - A^*_x) - \lambda_D) - 1\right]}{1 - \kappa^*_1 \rho_w} \tag{C.23}$$

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

C.1.4 Solution for the Dividend Paying Asset

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

$$\Delta d_{t+1} = \mu_d + \phi x_t + \pi\sigma_t\eta_{t+1} + \phi\varphi_c D_{t+1} + \varphi_u\sigma_t u_{t+1} \tag{C.24}$$

and the market return must satisfy,

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

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

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

which after some algebraic manipulation equals to,

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

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

$$A_{x,m} \quad = \quad \frac{\left(\phi - \frac{1}{\psi}\right) + \kappa_{1,m}A_{w,m}\tau_x}{1 - \kappa_{1,m}\rho} \tag{C.25}$$

$$A_{\sigma,m} \quad = \quad \frac{(\theta-1)(\kappa_1\nu - 1)A_\sigma + \frac{1}{2}\left[(\kappa_1 A_{x,m}\varphi_e - \lambda_e)^2 + (\pi - \lambda_\eta)^2 + \varphi_u^2\right]}{1 - \kappa_{1,m}\nu} \tag{C.26}$$

$$A_{w,m} \quad = \quad \frac{(\theta-1)(\kappa_1\rho_w - 1)A_w + \ell_1\Big[\Phi[\phi\varphi_c + \kappa_{1,m}A_{x,m}\varphi_x - \lambda_D] - 1\Big]}{\theta(1 - \kappa_{1,m}\rho_w)} \tag{C.27}$$

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

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

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

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

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

Bibliography

Bali, T. and Zhou, H. (2012), "Risk, uncertainty, and expected returns," .

Bansal, R. and Ochoa, M. (2011), "Temperature, Aggregate Risk, and Expected Returns," .

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

Bansal, R., Dittmar, R. F., and Lundblad, C. T. (2005a), "Consumption, dividends, and the cross section of equity returns," *The Journal of Finance*, 60, 1639–1672.

Bansal, R., Khatchatrian, V., and Yaron, A. (2005b), "Interpretable asset markets?" *European Economic Review*, 49, 531–560.

Bansal, R., Kiku, D., and Yaron, A. (2007a), "Risks for the long run: Estimation and inference," *Manuscript, Department of Economics, Duke University, Durham NC*.

Bansal, R., Kiku, D., and Yaron, A. (2007b), "Risks for the long run: Estimation and inference," *Manuscript, Department of Economics, Duke University, Durham NC*.

Bansal, R., Kiku, D., and Yaron, A. (2012a), "An Empirical Evaluation of the Long-Run Risks Model for Asset Prices," *Critical Finance Review*, 1, 183–221.

Bansal, R., Kiku, D., Shaliastovich, I., and Yaron, A. (2012b), "Volatility, the Macroeconomy and Asset Prices," .

Barlevy, G. (2004), "The cost of business cycles and the benefits of stabilization: a survey," .

Bazdrech, S., Belo, F., and Lin, X. (2009), "Labor Hiring, Investment and Stock Return Predictability in the Cross Section," .

Bekaert, G., Engstrom, E., and Xing, Y. (2009), "Risk, uncertainty, and asset prices," *Journal of Economic Dynamics and Control*, 91, 59–82.

Bentolila, S. and Bertola, G. (1990), "Firing costs and labour demand: how bad is eurosclerosis?" *The Review of Economic Studies*, 57, 381–402.

Bhamra, H. S., Kuehn, L. A., and Strebulaev, I. A. (2009), "The levered equity risk premium and credit spreads: A unified framework," *Review of Financial Studies*.

Bloom, N. (2009), "The Impact of Uncertainty Shocks," *Econometrica*, 77, 623–685.

Bloom, N., Floetotto, M., Jaimovich, N., Saporta-Eksten, I., and Terry, S. (2011), "Really uncertain business cycles," .

Bollerslev, T., Tauchen, G., and Zhou, H. (2009), "Expected stock returns and variance risk premia," *Review of Financial Studies*, 22, 4463–4492.

Bollerslev, T., Xu, L., and Zhou, H. (2012), "Stock Return and Cash Flow Predictability: The Role of Volatility Risk," *Available at SSRN 2177046*.

Button, P. (1990), "The cost of labour turnover: an accounting perspective," *Labour Economics and Productivity*, 2, 245–73.

Caballero, R. and Engel, E. (1993), "Microeconomic adjustment hazards and aggregate dynamics," *The Quarterly Journal of Economics*, 108, 359–383.

Caballero, R. J., Engel, E. M. R. A., and Haltiwanger, J. (1997), "Aggregate Employment Dynamics: Building From Microeconomic Evidence," *The American Economic Review*, 87, 115–137.

Campbell, J. Y., Giglio, S., Polk, C., and Turley, R. (2012), "An intertemporal capm with stochastic volatility," .

Cascio, W. (1991), *Costing human resources*, South-Western Educational Publishing.

Chan, L. K., Lakonishok, J., and Sougiannis, T. (2001), "The Stock Market Valuation of Research and Development Expenditures," *Journal of Finance*, 56, 2431—2456.

Chen, H., Kacperczyk, M., and Ortiz-Molina, H. (2011), "Labor unions, operating flexibility, and the cost of equity," *Journal of Financial and Quantitative Analysis*, 46, 25–58.

Chow, C. and Tsitsiklis, J. (1991), "An optimal one-way multigrid algorithm for discrete-time stochastic control," *Automatic Control, IEEE Transactions on*, 36, 898–914.

Cohen, R., Gompers, P., and Vuolteenaho, T. (2002), "Who underreacts to cash-flow news? Evidence from trading between individuals and institutions," *Journal of Financial Economics*, 66, 409–462.

Cooper, R. and Willis, J. (2009), "The cost of labor adjustment: Inferences from the gap," *Review of Economic dynamics*, 12, 632–647.

Crocker, T. D. and Horst, R. L. (1981), "Hours of Work, Labor Productivity, and Environmental Conditions: A Case Study," *The Review of Economics and Statistics*, 63, 361–368.

Curriero, F., Heiner, K., Samet, J., Zeger, S., Strug, L., and Patz, J. (2002), "Temperature and mortality in 11 cities of the eastern United States," *American Journal of Epidemiology*, 155, 80.

Danthine, J.-P. and Donaldson, J. B. T. (2002), "Labour Relations and Asset Returns," *The Review of Economic Studies*, 69, 41–64.

Dell, M., Jones, B. F., and Olken, B. A. (2009a), "Climate Shocks and Economic Growth: Evidence from the Last Half Century," *NBER Working Paper*, 14132.

Dell, M., Jones, B. F., and Olken, B. A. (2009b), "Temperature and Income: Reconciling New Cross-Sectional and Panel Estimates," *American Economic Review*, 99, 198–204.

Dixit, A. (1993), *The art of smooth pasting*, vol. 2, Routledge.

Dolfin, S. (2006), "An examination of firms' employment costs." *Applied Economics*, 38, 861–878.

Donangelo, A. (2011), "Labor Mobility: Implications for Asset Pricing," *Available at SSRN 1715232*.

Drechsler, I. and Yaron, A. (2009), "What's vol got to do with it," Working Paper.

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

Eraker, B. and Shaliastovich, I. (2008), "An equilibrium guide to designing affine pricing models," *Mathematical Finance*, 18, 519–543.

Fairfield, P., Whisenant, J., and Yohn, T. (2003), "Accrued earnings and growth: Implications for future profitability and market mispricing," *The Accounting Review*, 78, 353–371.

Fama, E. and French, K. (1993), "Common risk factors in the returns on stocks and bonds," *Journal of financial economics*, 33, 3–56.

Fama, E. and French, K. R. (1997), "Industry costs of equity," *Journal of Financial Economics*, 43, 153–193.

Fama, E. and MacBeth, J. (1973), "Risk, return, and equilibrium: Empirical tests," *The Journal of Political Economy*, pp. 607–636.

Fama, E. F. and French, K. R. (1996), "Multifactor explanations of asset pricing anomalies," *The Journal of Finance*, 51, 55–84.

Fama, E. F. and French, K. R. (2008), "Dissecting Anomalies," *Journal of Finance*, 63, 1653–1678.

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

Hall, R. E. and Jones, C. I. (1999), "Why do some countries produce so much more output per worker than others?" *The quarterly journal of economics*, 114, 83–116.

Hamermesh, D. S. and Pfann, G. A. (1996), "Adjustment Costs in Factor Demand," *Journal of Economic Literature*, 34, 1264–1292.

Hansen, L., Heaton, J., and Li, N. (2008), "Consumption strikes back? Measuring long-run risk," *Journal of Political Economy*, 116, 260–302.

Haugen, R. and Baker, N. (1996), "Commonality in the determinants of expected stock returns," *Journal of Financial Economics*, 41, 401–439.

Heston, A., Summers, R., and Aten, B. (2009), "Penn World Table Version 6.3," Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania.

Hinkin, T. R. and Tracey, J. B. (2000), "The Cost of Turnover," *Cornell Hotel and Restaurant Administration Quarterly*, 41, 14–21.

Hou, K. and Robinson, D. T. (2006), "Industry Concentration and Average Stock Returns," *The Journal of Finance*, 61, 1927–1956.

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

IPCC (2007a), "Climate Change 2007: Synthesis Report," Geneva, Switzerland.

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

IPCC (2012), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, Cambridge University Press.

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

Kandel, S. and Stambaugh, R. F. (1990), "Expectations and volatility of consumption and asset returns," *Review of Financial Studies*, 3, 207–232.

Kydland, F. (1984), "Labor-force heterogeneity and the business cycle," in *Carnegie-Rochester Conference Series on Public Policy*, vol. 21, pp. 173–208, Elsevier.

Li, D. (2011), "Financial Constraints, R&D Investment, and Stock Returns," *Review of Financial Studies*, 24, 2974–3007.

Lin, X. (2012), "Endogenous technological progress and the cross-section of stock returns," *Journal of Financial Economics*, 103, 411–427.

Lucas, R. (1987), *Models of business cycles*, Basil Blackwell New York.

Lustig, H., Van Nieuwerburgh, S., and Verdelhan, A. (2009), "The wealth-consumption ratio," Working Paper.

Matsa, D. A. (2010), "Capital Structure as a Strategic Variable: Evidence from Collective Bargaining," *The Journal of Finance*, 65, 1197–1232.

Meese, G., Kok, R., Lewis, M., and Wyon, D. (1982), "Effects of Moderate Cold and Heat Stress on Factory Workers in Southern Africa," *South Africa Journal of Science*, 78, 189–197.

Merz, M. and Yashiv, E. (2007), "Labor and the market value of the firm," *The American Economic Review*, 97, 1419–1431.

Mincer, J. (1962), "On-the-job training: Costs, returns, and some implications," *The Journal of Political Economy*, pp. 50–79.

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

Nordhaus, W. D. (2010), "Economic aspects of global warming in a post-Copenhagen environment," *Proceedings of the National Academy of Sciences*, pp. 1–6.

Nordhaus, W. D. and Boyer, J. (2003), *Warming the world: economic models of global warming*, MIT press.

Novy-Marx, R. (2011), "Operating Leverage," *Review of Finance*, 15, 103–134.

Oi, W. Y. (1962), "Labor as a quasi-fixed factor," *Journal of Political Economy*, 70, 538–555.

Parsons, D. O. (1986), "The employment relationship: Job attachment, work effort, and the nature of contracts," in *Handbook of Labor Economics*, eds. O. C. A. Layard and Richard, pp. 789–848 T2 –, Elsevier.

Patton, A. and Timmermann, A. (2010), "Monotonicity in asset returns: New tests with applications to the term structure, the CAPM, and portfolio sorts," *Journal of Financial Economics*, 98, 605–625.

Pfann, G. A. and Verspagen, B. (1989), "The structure of adjustment costs for labour in the Dutch manufacturing sector," *Economics Letters*, 29, 365–371.

Piazzesi, M. and Schneider, M. (2007), "Equilibrium Yield Curves," *in Daron Acemoglu, Kenneth Rogoff, and Michael Woodford, (eds.) NBER Macroeconomics Annual 2006*.

Pindyck, R. S. (2012), "Uncertain outcomes and climate change policy," *Journal of Environmental Economics and Management*.

Pratt, R. (2011), "A Structural Model of Human Capital and Leverage," .

Rasmussen, T. N. (2004), "Macroeconomic Implications of Natural Disasters in the Caribbean," IMF Working Papers 04/224, International Monetary Fund.

Rosen, S. (1968), "Short-Run Employment Variation on Class-I Railroads in the U.S., 1947-1963," *Econometrica*, 36, 511–529.

Rust, J. (1996), "Numerical dynamic programming in economics," *Handbook of computational economics*, 1, 619–729.

Schmalz, M. C. (2011), "Managing Human Capital Risk," pp. 1–41.

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

Stern, N. H. (2006), *Stern Review: The economics of climate change*, vol. 30, HM treasury London.

Stokey, N. (2009), *The economics of inaction: Stochastic control models with fixed costs*, Princeton University Press.

Titman, S., Wei, K., and Xie, F. (2004), "Capital investments and stock returns," *Journal of Financial and Quantitative Analysis*, 39, 677—700.

Weil, P. (1990), "Nonexpected utility in macroeconomics," *The Quarterly Journal of Economics*, 105, 29–42.

Weitzman, M. L. (2009), "On Modeling and Interpreting the Economics of Catastrophic Climate Change," *The Review of Economics and Statistics*.

Wolak, F. A. (1989), "Testing inequality constraints in linear econometric models," *Journal of Econometrics*, 41, 205–235.

Zivin, J. G. and Neidell, M. J. (2010), "Temperature and the allocation of time: Implicationf for climate change," NBER Working Paper 15717.

Biography

Juan Marcelo Ochoa-Coloma was born in La Paz, Bolivia on July 16th, 1977. He graduated, with honors, from the Universidad Católica Boliviana San Pablo, in 2002 with a Bachelor of Arts in Economics. He holds a Master in Economics from the Universidad de Chile, earned in 2006. Before joining the graduate program at Duke University, he worked as an Economic Analyst at the Central Bank of Chile's Research Department. He earned a Master of Arts in Economics from Duke University in 2008, and he is planning on graduating from Duke University with Ph.D. degree in Economics in spring of 2013.