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What Do Financial Markets Reveal about Global Warming?

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1. Introduction

Evidence in support of the notion of global warming is accumulating. In its most comprehensive and up-to-date scientific assessment of climate change, the 2007 Nobel Peace Prize recipient Intergovernmental Panel on Climate Change (IPCC) concludes that "Warming of the climate system is unequivocal" (IPCC, 2007, Working Group I Report *Summary for Policymakers*, p. 5).

The majority of the research concerning the economic impact of global warming has emphasized the future effect on production or cash flows of an *abrupt* change in climate to occur sometime after the year 2050.[1] Prominent examples are the work of Mendelsohn et al. (2000) and Nordhaus and Boyer (2000) examining and aggregating the output losses by sector, and the work of Horowitz (2001) and Nordhaus (2006) identifying aggregate output losses with a reduced-form cross-sectional approach, occurring once temperatures increase by at least 2.5 to 3.0 degrees Celsius. The highest estimate of the adverse impact of a 3.0 degrees Celsius increase in temperature is a three percent permanent decrease in GDP.

After evaluating various climate-change mitigation strategies, IPCC estimates that stabilizing CO_2 concentrations and limiting the long-term temperature rise may result in a 0.12 percent reduction in the annual growth rate of global GDP. This estimate provides a threshold for climate-change mitigation policies: policies are worth considering only if the negative economic impact of global warming represents a greater cost than the 0.12 percent reduction in GDP growth or a present value loss of 4.56 percent of wealth.[2] Because the GDP losses due to global warming of up to three percent occur so far in the future, the present value of these losses is usually too small to justify aggressive mitigation policies. Tol (2008, p.5) concisely summarizes the state of research by stating "It is therefore no surprise that cost-benefit analyses of climate change recommend only limited greenhouse gas emission reduction."

We take a different approach in this paper and focus on the economic impact of *gradual* temperature change. This is motivated by the recent findings of IPCC. IPCC (2007) points out that gradual global warming can increase the intensity and frequency of extreme events. With gradual climate change, IPCC projects that drought, heavy precipitation, heat waves, extreme sea levels, and intense tropical cyclone activity will likely increase (see also NACC, 2000 and Stern, 2007). Figure 1 illustrates the increasing prevalence of extreme weather events with a scatter graph of the annual temperature and the climate extreme index (CEI) from the National Climatic Data Center in the U.S. over the 1946 to 2007 period.[3]

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[1] The direct impact on production of a rise in mean temperature staying within 2.5 degrees Celsius is usually small and even positive. See Tol (2008) for an excellent review.

[2] See Section 6 below for details.

[3] The CEI was first introduced in early 1996 with the goal of summarizing and presenting a complex set of multivariate and multidimensional climate changes in the United States. It is based on an aggregate set of conventional climate extreme indicators which, at the present time, include the following types of data: monthly

Figure 1. Temperatures and Extreme Weather Events.
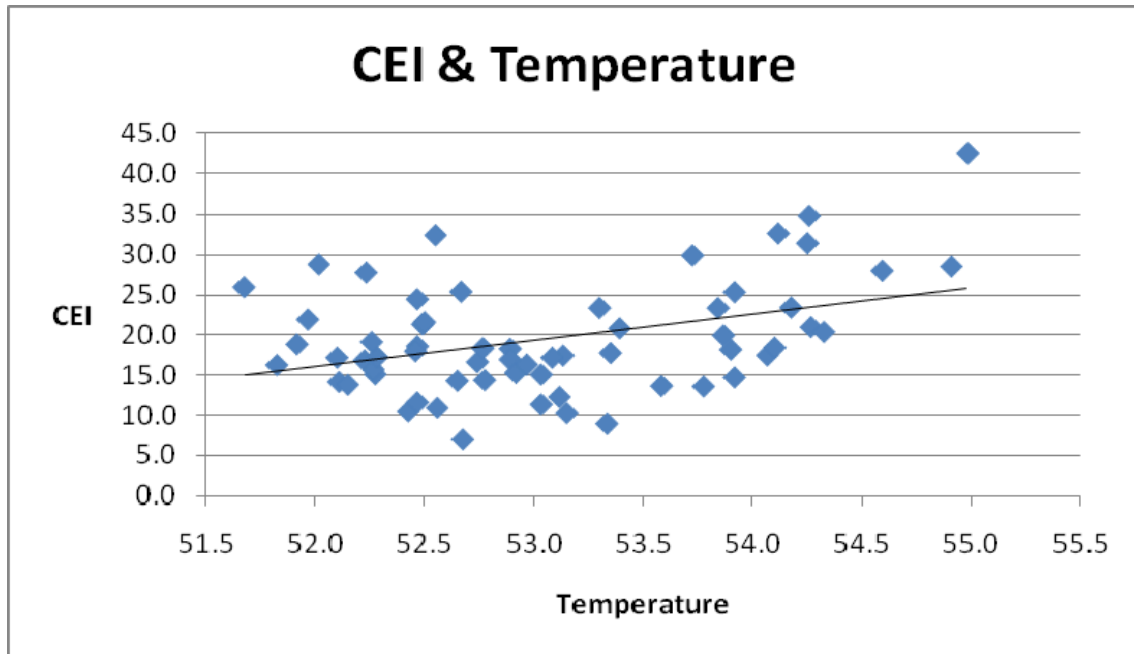
Figure 1. For each of the years over the 1946 to 2007 period (represented by the square dots), Figure 1 illustrates the prevalence of extreme weather in relation to the annual temperature average for the year (in degrees Fahrenheit). The extreme weather prevalence is measured by the Climate Extreme Index (CEI) from the National Climatic Data Center in the U.S. The CEI was introduced in early 1996 and is based on an aggregate set of conventional extreme-climate indicators which, at the present time, include the following types of data: monthly maximum and minimum temperature, daily precipitation, monthly Palmer Drought Severity Index (PDSI), and landfalling tropical storm and hurricane wind velocity.

Extreme weather events typically adversely affect production and cash flows of firms. Stern (2007) points out that extreme events (such as storms, floods, droughts, and heat waves) could lead to significant infrastructure damage and faster capital depreciation, and that increases in extreme events will be particularly costly for developed economies because they invest a considerable amount in fixed capital each year (a good example is Hurricane Katrina).[4] Stern (2007) estimates that the annual losses due to

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maximum and minimum temperature, daily precipitation, the monthly Palmer Drought Severity Index (PDSI), and land-falling tropical storm and hurricane wind velocity. Each indicator has been selected based on its reliability, length of record, availability, and its relevance to changes in climate extremes.

[4] The 6/30/08 (pre-hurricane-Ike) issue of the Wall Street Journal reports that "Bad weather has cost U.S. property insurers more than $5 billion so far in second-quarter catastrophe-related claims—equal to about three-quarters of all catastrophe claims during 2007—and could push the industry to an underwriting loss."

extreme weather events have been around 0.2 percent of World GDP since the 1990s, and that the annual losses could reach 0.5 – 1.0 percent of world GDP by the middle of the century.[5]

It is well known that impacts of global warming on cash flows could also be highly *uncertain*, which partly stems from considerable uncertainty about the magnitude of global warming, with the range of possible magnitudes involving differences of several hundred percent. This is illustrated by the IPCC's widely-quoted estimates for the possible increase in global mean temperature. Its best estimate for global average surface warming at the end of the 21st century ranges from 1.8°C (with 66 percent confidence interval from 1.1°C to 2.9°C) to 4.0°C (with 66 percent confidence interval from 2.4°C to 6.4°C). Heal and Kriström (2002) argue that uncertainty is a central feature of climate change.

In brief, global warming (negatively) affects cash flows of firms in an uncertain fashion, acting as a (negative) supply shock. This shock should affect firms and economy not only by its impact on the level of cash flows, but also by its impact on the risk or uncertainty of cash flows and therefore the cost of capital. Global warming (as a supply shock) introduces a new risk factor into the economy. As a result, investors demand higher returns on risky assets such as stocks and corporate bonds. Higher returns represent a higher cost of capital to firms, which can have a profound and adverse impact on capital investment and economic growth. The negative link between the cost of capital and economic growth is well documented in the economics literature (see for instance Henry, 2003). Thus, ignoring global warming's impact on the cost of capital may significantly understate its economic impact. Yet a review of the literature shows that there has been no research concerning the impact of global warming on the cost of capital.[6] We explore here in detail the cost-of-capital link.

A related objective is to provide a detached assessment of possible costs of global warming: Since the scientific literature is not definitive concerning the magnitude of the welfare effects of global warming, the observable financial market impact of changes in the likelihood of global warming may provide an objective measure of the collective perception of some of the economic damages from global warming.

If global warming is economically important, the risk premium and loadings associated with the global-warming factor should be significantly different from zero. In particular, if climate-change impacts are generally adverse (losses due to extreme events and/or adjustment costs), we expect to see a *negative* premium, because (1) if climate-change impacts are adverse, increases in temperature should lead to

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[5] Aside from extreme events, Quiggin and Horowitz (2003) emphasize adjustment costs to climate change. They argue that costs of adjustment will arise if capital stocks: (i) are dependent on climate for their optimal location; and (ii) depreciate more slowly than is required to permit easy adjustment to a changing climate. See also Nordhaus (1991), Cline (1992), Mendelsohn, Nordhaus, and Shaw (1994), Fankhauser (1995), Tol (1995), Rosenthal, Gruenspecht, and Moran (1995), Moore (1998), Mendelsohn and Neumann (1999), Schlenker, Hanemann, and Fisher (2006), and IPCC (2007) for the various impact mechanisms of global warming,

[6] Kamstra, Kramer and Levi (2003) examine how temperature affects human mood and investor behavior, but not from the climate change perspective. Fankhauser and Tol (2005) study the impact of global warming on capital accumulation, but not from the cost of capital perspective.

lower returns for typical firms, and so the loadings on the global-warming factor should be generally negative; (2) to compensate for the additional risk, the equilibrium return should be higher, and with negative loadings this can only be achieved by a negative risk premium. In essence we conjecture that global warming is a risk factor that is priced because it affects investment opportunities in the sense of Merton (1973).

We employ two approaches to estimate the posited risk premium of a global warming factor. The first is the tracking portfolio approach of Lamont (2001). The advantage of this approach is that it does not force us to select an equilibrium asset pricing model and therefore may avoid model specification error. But this approach cannot provide us with an estimate of the loadings on a global warming factor and the impact on the cost of capital. We therefore also employ a second, more structural approach – the two-pass regression methodology proposed by Black, Jensen, and Scholes (1972) and Fama and MacBeth (1973), as amended by Shanken (1992), Lewellen, Nagel and Shanken (2009), and Shanken and Zhou (2007). Consistent with our conjecture, we find evidence suggesting that signals of global warming cause an increase in the cost of capital. Quantitatively this evidence suggests that the impact of global warming may be larger than previously thought.

The remainder of the paper is organized as follows: Section 2 discusses the theoretical perspective and states three testable hypotheses as well as presenting the appropriate expression for calculating the welfare loss. Section 3 briefly discusses the data. Section 4 presents a non-structural approach – the tracking portfolio approach – that does not involve specification of a particular asset pricing model and allows us to test two of the hypotheses, while Section 5 tests a third hypothesis and provides quantitative results in a structural context – applying the two-pass regression methodology to the standard Fama-French and CAPM asset pricing models. Section 6 investigates specifically the quantitative impact of climate change on the cost of capital, and Section 7 concludes the paper with a brief summary.

2. Theoretical Perspective and Hypotheses

A general perspective on the factors explaining asset returns is provided by the Merton (1973) model. Merton's model implies that excess returns are determined by the systematic risk of an asset, which in turn depends on the asset's sensitivity to both market returns and aggregate changes in investment opportunities. The application of the model is not straightforward because it provides no specifics about how to characterize aggregate changes in investment opportunities. Of the two most popular asset pricing models, the Sharpe-Lintner CAPM ignores the possibility of investment opportunity shifts, and the Fama-French Three-Factor model empirically captures investment opportunity shifts by means of a value and a size factor.

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In a steady state, climate cannot be considered a determinant of changes in investment opportunities. Particular weather realizations affect asset return realizations through standard channels but do not affect future investment opportunities. The nature of a transition period between climate states arising on account of global warming, however, is that potential changes in climate are both uncertain and persistent. Since climate strongly affects production and investment opportunities (see for instance Choinière and Horowitz, 2006), the climate changes associated with global warming would be key determinants of fluctuations in investment opportunities, and should be priced in the context of the Merton model.

We postulate that climate changes represent a priced Merton factor and check empirically if the implications of this view are confirmed by the data. The following hypotheses derive more or less directly from this postulate and will be the target of our empirical analysis in following sections.

HYPOTHESIS 1. *The global warming factor has a significant and negative risk premium.*

If the risk factor is priced, it should have a statistically and economically significant risk premium. Moreover, since the presumption is that most firms are negatively affected by increased warming (the factor loadings on the global warming factor are generally negative), the risk premium must be negative to ensure that riskier assets have higher average returns – a decrease in future investment opportunities is added on top of the initial negative weather shock; and firms whose investment opportunities are affected more are accordingly riskier.

The awareness of the possibility of global warming has increased over the last several decades and this can be taken to imply that changes in weather patterns may be increasingly thought as attributable to global warming and thus more persistent, implying a larger risk premium.

HYPOTHESIS 2. *The risk premium on the global warming factor increases (in absolute terms) over the global warming period starting in 1976.*

We here take as the start of global warming the year 1976 as claimed by IPCC (2007).

One issue with global warming, potentially contributing to its surrounding controversy, is that it may have an uneven impact. In particular, some industries (see IPCC, 2007 and Quiggin and Horowitz, 2003) are more vulnerable: *agriculture and forestry, transportation, retail, commercial services, tourism, insurance, those industries dependent on climate-sensitive inputs (such as food processing), and industries with long-lived capital assets.* If global warming is truly a risk factor, the industries that are

more sensitive to climate changes should have higher loadings on the global warming factor and, accordingly, higher required returns.

> **HYPOTHESIS 3.** *The industries that are considered to be more vulnerable to global warming have higher loadings on the global warming factor.*

To address these hypotheses with some accuracy we ask a rather narrower question than the question of whether global warming affects cost of capital. For reasons of implementation we ask: *How does news about changes in average U.S. temperatures over the period classified by IPCC as the "global warming period" affect the cost of capital for U.S. equities?* Our belief is that by focusing on a case for which we have accurate data and a clearly defined set of questions, we can begin to obtain insights and ideas that are more generally applicable to the global case.

As an implication, contingent on confirmation of the above hypotheses, we can formulate a measure for the losses stemming from gradual climate change's effect on the cost of equity capital.

> **PROPOSITION.** **(A)** *The aggregate change in the cost of equity capital due to the global warming factor equals the value-weighted average global warming beta times the global warming risk premium.* **(B)** *The aggregate losses in average shareholder value can be approximated by the average change in the cost of equity capital times the average price-dividend ratio.*

Part (B) of the proposition follows from a Gordon growth model approximation for equity value and by differentiating with respect to the cost of capital.

3. Data

IPCC (2007) points out that global warming seems to have been taking place in two distinct phases, the first between 1910 and 1945, and the second from 1976. The decrease in the global temperature between 1945 and 1976 may be due to substantial sulphur emissions and changed sunspot activity in this period. Therefore, the post-WWII period offers two distinct periods to examine, the pre-warming of 1946 to 1975 and the global warming of 1976 to 2008. We omit the *pre*-1946 period, avoiding the Great Depression and world war periods, to obtain more reliable estimates of the risk premium of global warming.

In terms of location, we limit ourselves to the United States. Whereas global warming is by definition a world-wide phenomenon, there are complicated distribution issues that we are not prepared to

address. Additionally, the required weather and financial-market data are available for the U.S. and are uniformly accurate – in particular, climate measures, macro and risk factor data, and industry-specific equity portfolio returns. The portfolio returns and Fama-French factor data are from Kenneth French's website.[7] The macro variables data are from the Federal Reserve Bank - St. Louis. The temperature time series is the U.S. average temperature series obtained from the National Climatic Data Center.

4. Economic Tracking Portfolios: A Non-Structural Approach

Asset returns are driven by changing information, "news", about future cash flows and discount rates. What matters for our purposes is the news concerning future global warming contained in the current observation. We could use a structural model to estimate the news concerning future global warming. But doing so results in a joint test of the validity of the model for what constitutes news and the validity of our hypothesis that global warming matters for financial markets. To circumvent this issue, we use the economic tracking portfolio approach proposed by Breeden, Gibbons, and Litzenberger (1989) and Lamont (2001), and recently applied by Vassalou (2003). Importantly, this a-theoretical approach further allows us to estimate the risk premium of global warming without imposing a particular model of asset pricing.

4.1. A Statistical Model of Climate News

For measurement purposes we equate climate change and global warming with a change in average temperatures. The extant temperature modeling literature (see IPCC, 2007) often uses structural atmospheric models. As Campbell and Diebold (2005) point out, however, although such an approach may be best for modeling and forecasting for a short horizon, it is not at all obvious that it is best for longer horizons. Successful modeling and forecasting does not necessarily require a structural model, and in the last several decades statisticians and econometricians have made great strides in the nonstructural modeling and forecasting of time series trend, seasonal, cyclical, and noise components.

We therefore follow Campbell and Diebold (2005) and take a simple time-series approach to modeling and forecasting temperature.[8] Our time-series model is the daily temperature model of Campbell and Diebold (2005) amended to deal with monthly observations. We include a linear time trend and 11 monthly seasonal dummies for our monthly temperature data. That is,

$$T_t = C + A \cdot trend_t + \sum_{i=1}^{11} S_i \cdot seasonal_i + error_t \ , \tag{1a}$$

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[7] http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/.
[8] See also Harvey (1989), Seater (1993), and Visser and Molenaar (1995).

with T_t representing the average temperature in month t, and $error_t$ representing the effects of all other

variables. Defining $CT_{t+12} = \dfrac{1}{12}\sum_{i=1}^{12} T_{t+i}$ as the average temperature over the next year, we have

$$CT_{t+12} = c + a \cdot trend_t + e_{t+12} \ ,\tag{1b}$$

where $c = C + \dfrac{1}{12}\sum_{i=1}^{12} iA + \dfrac{1}{12}\sum_{i=1}^{11} S_i$, $a = A$, and $e_{t+12} = \dfrac{1}{12}\sum_{i=1}^{12} error_{t+i}$, captures the effects of all other

variables between t+1 and t+12. Therefore,

$$E_{t-1}(CT_{t+12}) = c + a \cdot trend_t + E_{t-1}(e_{t+12}) \ .\tag{1c}$$

Now define $\Delta E_t(CT_{t+12}) = E_t(CT_{t+12}) - E_{t-1}(CT_{t+12})$ as the news component in the temperature

observation in month t. Then we have the tautology

$$CT_{t+12} \equiv E_{t-1}(CT_{t+12}) + \Delta E_t(CT_{t+12}) + \omega_{t+12},\tag{2}$$

which decomposes the annual temperature at the end of the following year in a previously expected

component, a news component, and noise, with noise $\omega_{t+12} \equiv e_{t+12} - E_t(e_{t+12})$.

4.2. An Economic Tracking Portfolio for Climate Change

      If global warming matters for asset pricing, innovations in excess returns of base assets reflect

innovations in expectations about future global warming. That is,

$$\Delta E_t(CT_{t+12}) = b\tilde{R}_t + \eta_t \ ,\tag{3}$$

where $\tilde{R}_t$ represents a column vector of unexpected returns $\tilde{R}_t = R_t - E_{t-1}(R_t)$, with R_t a column vector

of excess returns of base assets in month t, and η_t the component of news that is orthogonal to the

unexpected returns of the base assets.

      Assume that the base asset return in month t is a linear function of Z_{t-1}, a vector of conditioning

economic variables known at period t-1, and that e_{t+12} is a linear function of Z_{t-1}, and Z'_{t-1} a vector of

conditioning climate variables known at period t-1. That is, $E_{t-1}(R_t) = d \cdot Z_{t-1}$

and $E_{t-1}(e_{t+12}) = f \cdot Z_{t-1} + g \cdot Z'_{t-1}$. Then we have from equations (1b), (2), and (3) that

$$CT_{t+12} = E_{t-1}(CT_{t+12}) + \Delta E_t(CT_{t+12}) + \omega_{t+12}$$

$$= c + a \cdot trend_t + fZ_{t-1} + gZ'_{t-1} + b(R_t - dZ_{t-1}) + \eta_t + \omega_{t+12},$$

or

$$CT_{t+12} = c + a \cdot trend_t + gZ'_{t-1} + bR_t + eZ_{t-1} + \varepsilon_{t+12} \ ,\tag{4}$$

with $e = -bd + f,$ and $\varepsilon_{t+12} = \eta_t + \omega_{t+12}$.

Tracking portfolio returns are defined here as the "factor mimicking" portfolios of excess returns $r_t = bR_t$. The OLS regression given by equation (4) can be used to estimate the portfolio weights b so as to obtain bR_t, the tracking portfolio returns of expectations about global warming, the global warming factor.

The unconditional mean of the tracking portfolio returns $bE(R_t)$ represents the risk premium of the global warming factor (see Lamont, 2001 and Vassalou, 2003). The intuition is that the estimated coefficients b represent the base asset loadings on the temperature news. The portfolio with weights b on the base assets has a mean excess return $bE(R_t)$ that reflects the risk due to temperature news and can be interpreted as the risk premium on the global warming factor. If global warming is economically important, the risk premium associated with global warming should be significantly different from zero. Furthermore, if climate-change impacts are generally adverse (losses due to extreme events and/or higher adjustment costs), we expect to see a negative premium: because the loadings on the global-warming factor should be normally negative and to compensate for the additional risk the equilibrium return should be higher, which, with negative loadings, can only be achieved by a negative risk premium.

We focus on news concerning next year's cumulative average temperatures (CT_{t+12}). The implicit assumption is that asset returns are affected by news regarding global warming over the upcoming one-year period. This is a reasonable simplifying assumption because, even if asset returns are affected by global warming news over a longer horizon, we would expect that much of this news pertains also to next year's global warming. We largely follow Vassalou (2003) and use the six Fama-French size/book-to-market portfolios as the base assets.[9] To obtain the conditioning variables – the Z_{t-1} in equation (4) – we again follow Vassalou (2003) and use macro variables which are known to predict equity returns. They are the risk-free rate (RF), the term premium (TERM), the default premium (DEF), and a detrended wealth variable (CAY) computed by Lettau and Ludvigson (2001). We use the lagged average temperature over the past one year as the single climate control variable in Z'_{t-1}.

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[9] Although Vassalou (2003) also includes the term premium and the default premium as her base assets in *R*, we do not do so for two reasons. First, with our monthly data we find strong first-order autocorrelation in these two time series. As a result, including them as base assets introduces strong multicollinearity into Eq. (4). Note that the one-month lagged term and default premium are used as the conditioning variables in *Z*. The resulting tracking portfolio is dominated by time-series variation in the default premium, and has little value for tracking the variation in temperature. The results are available upon request. Second, in theory, we want to extract the news about future global warming that the stock market perceives and then estimate the risk premium on stocks. Therefore, the bond portfolio returns are not necessary as base assets. They are still useful as conditioning variables because the literature shows that they can predict equity returns (see Fama and French, 1988).

4.3. The Trend in Temperature

One potential misspecification of the model in equation (1a) is that the temperature series may have a stochastic trend instead of a deterministic trend. We therefore conduct a unit root test. IPCC (2007) indicates that global warming is a post-1976 phenomenon. Therefore, if there is a deterministic trend in temperature, it should be a broken trend. This observation motivates us to consider an econometric procedure developed by Perron (1997), which tests a stochastic trend against a broken deterministic trend.

Under the specific model we consider, a change in the slope is allowed and both segments of the trend function are joined at the time of the break. Following Perron (1997), we employ a two-step procedure. First, the temperature series is detrended using the following regression,

$$T_t = \mu + \beta \cdot trend_t + \delta \cdot DT_t^* + \overline{T}_t , \tag{5}$$

where $DT_t^* = trend_t - TB$ if $trend_t > TB$, and 0 otherwise, with TB the (unknown) time at which the break in the trend occurs; $\overline{T}_t$ is the detrended temperature series. The test is performed on $\overline{T}_t$ using the t-statistic for $\alpha = 1$ in the following regression:

$$\overline{T}_t = \alpha \overline{T}_{t-1} + \sum_{i=1}^{k} c_i \Delta \overline{T}_{t-i} + e_t . \tag{6}$$

In these regressions, TB and the truncation lag parameter k are treated as unknown. TB is selected as the value which minimizes the t-statistic for testing $\alpha = 1$: $t_{\hat{\alpha}}$. The asymptotic critical values of $t_{\hat{\alpha}}$ under the null (unit-root) hypothesis are provided by Perron (1997). K is obtained from the *t-sig* procedure which selects the value of k (say k^*) such that the coefficient on the last lag in an autoregression of order k^* is significant and that the last coefficient in an autoregression of order greater than k^* is insignificant, up to a predetermined maximum (here we choose 24 months as the maximum lag).

The estimation results are reported in Table 1. The data-dependent procedure chooses TB to be *December 1976*, and k to be *22*. With these values, $t_{\hat{\alpha}}$ is minimized. Its value of -5.55 is significant at the 1% level and implies rejection of the unit-root hypothesis for the temperature series. Therefore, the specification assumed in equation (1a) is considered to be appropriate. To be consistent with the general literature (i.e. IPCC, 2007), we use *January 1976* as our break point.

Table 1. Broken Trend in the Temperature Series: 1946:1-2008:6

Results for the Perron test to find the break point of a time series trend. The temperature series T_t is detrended using $T_t = \mu + \beta \cdot trend_t + \delta \cdot DT_t^* + \overline{T}_t$, where $DT_t^* = trend_t - TB$ if $trend_t > TB$, and 0 otherwise; TB is the (unknown) time at which the break in the trend occurs; $\overline{T}_t$ is the detrended

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temperature series. The test is performed on $\overline{T}_t$ using the t-statistic $t_{\hat{\alpha}}$ for $\alpha = 1$ in:

$$\overline{T}_t = \alpha \overline{T}_{t-1} + \sum_{i=1}^{k} c_i \Delta \overline{T}_{t-i} + e_t$$

; k is the number of lags of the detrended temperature. TB is selected as

the value which minimizes $t_{\hat{\alpha}}$. The asymptotic critical values of $t_{\hat{\alpha}}$ under the null (unit-root)

hypothesis listed here are from Perron (1997). k is selected by the t-sig procedure which selects

the value of k (say k*) such that the coefficient on the last lag in an autoregression of order k* is

significant and that the last coefficient in an autoregression of order greater than k* is insignificant,

up to a predetermined maximum (we select 24 months as the maximum lag).

TB	k	$t_{\hat{\alpha}}$	
1976:9	22	-5.55	

Critical Values for $t_{\hat{\alpha}}$

	1%	5%	10%
For 200 obs.	-5.28	-4.65	-4.38
infinite sample	-4.91	-4.36	-4.07

$\hat{\alpha}$	$\hat{\mu}$	$\hat{\beta}$	$\hat{\delta}$
0.025	52.863	-0.001	0.006

4.4. Empirical Results

Table 2 presents the construction and diagnostic tests of the global warming factor mimicking
tracking portfolios based on equation (4) with the six Fama-French size-BM portfolios as the base assets
and the macro variables used also by Vassalou (2003) as conditioning variables. The t-ratios are based on
Newey-West HAC standard errors with the lag parameter set equal to 12.

Table 2. Tracking Portfolios and Diagnostic Tests

The results for the regression of eq. (4), $CT_{t+12} = c + a \cdot trend_t + gZ'_{t-1} + bR_t + eZ_{t-1} + \varepsilon_{t+12}$, are in
Panel A, where CT_{t+12} represents the average annual temperature, $R_t = (SL_t, SM_t, SH_t, BL_t, BM_t, BH_t)'$ represents the excess returns of the Fama-French size-BM portfolios defined in Table 1. $Z_{t-1} = (RF_t, DEF_{t-1}, TERM_{t-1} CAY_{t-1})'$, which are, respectively, the risk free rate, the lagged default
risk premium, the lagged term premium, and the lagged Cay factor from Lettau and Ludvigson.
Z'_{t-1} is our lagged climate gauge. Panel B provides the R-square of the regression in eq. (7),
$CT_{t+12} - E_{t-1}(CT_{t+12}) = c_1[bR_t - E(bR_t | Z_{t-1})] + u_{t+12}$, forecasting the temperature news based on the
coefficient on R_t from Panel A. Panel C presents the average return on portfolio R_t with the
weights given by the coefficient estimates in Panel A.

| | 1976:1-2007:6 | | 1946:1-1975:12 | |

Panel A. Tracking Portfolio Regressions

	Coeff	*t-ratio*	Coeff	*t-ratio*
SL_t	0.033	*2.24*	0.015	*0.97*
SM_t	0.018	*0.49*	-0.046	*-1.81*
SH_t	-0.080	*-2.70*	-0.008	*-0.37*
BL_t	0.011	*0.54*	-0.001	*-0.05*
BM_t	-0.019	*-0.84*	0.014	*0.87*
BH_t	0.025	*1.24*	0.018	*1.18*
Constant	55.008	*9.75*	58.613	*8.68*
Trend	0.006	*4.75*	-0.004	*-1.58*
CT_{t-12}	-0.121	*-1.08*	-0.087	*-0.65*
RF_t	1.131	*1.88*	0.606	*0.78*
DEF_{t-1}	0.528	*1.74*	0.654	*2.70*
$TERM_{t-1}$	-0.150	*-2.21*	-0.080	*-0.54*
CAY_{t-1}	-4.620	*-0.55*	-9.403	*-1.32*
Adj-R^2	0.49		0.18	
χ^2 p-value	0.00		0.01	

Panel B. Lower Bounds of Tracking Portfolio Explanatory Power

Lower Bound	0.049		0.038	

Panel C. The means of the Tracking Portfolio Returns

Mean	-0.047	*-4.15*	-0.006	*-1.22*

The columns labeled "1976:1-2007:6" represent the results for the IPCC global warming period. The coefficient estimates in Panel A indicate that SL and SH have significant tracking ability for future global warming. This seems to be reasonable because small companies are generally more sensitive to global warming or any other risk. Growth firms may potentially benefit from global warming as they do not have their capital in place yet (SL coefficient > 0). Value firms face adjustment costs, as argued by Quiggin and Horowitz (2003), since their capital is already in place (SH coefficient < 0). In the next panel, the chi-square test rejects the hypothesis that the coefficients on the base assets are jointly zero at the 0% level, indicating that the base assets have significant tracking ability.

We next evaluate the ability of the tracking portfolio to forecast temperature changes for the upcoming year, with the following regression suggested by Lamont (2001):

$$CT_{t+12} - E_{t-1}(CT_{t+12}) = h \cdot [bR_t - E(bR_t \mid Z_{t-1})] + u_{t+12} \tag{7}$$

The R-square from this regression provides an indication of the tracking ability of the factor mimicking portfolio. It gives a *lower bound* for the tracking ability because, from equation (2), the left-hand side of equation (7) is only a noisy measure of the news component in the recent temperature observation. The R-square in Panel B is 4.9% for the global warming period. So it appears that our tracking portfolio has significant ability for tracking global warming news. In comparison, the ability of the tracking portfolios to track news related to future GDP growth in Vassalou (2003) varies between 3% and 8%. Panel C provides the mean of the tracking portfolio return, which is -0.047 percent with t-statistic of -4.15 for the 1976:1-2007:6 period. Therefore, consistent with Hypothesis 1, the risk premium on global warming is significantly negative. Figure 2 shows raw average temperatures and the global warming factor series for 1976 to 2007.[10]

Figure 2. Descriptive Statistics for Temperatures and the Global Warming Factor.

Figure 2a. Annual Average Raw Temperatures, CT_{t+12}

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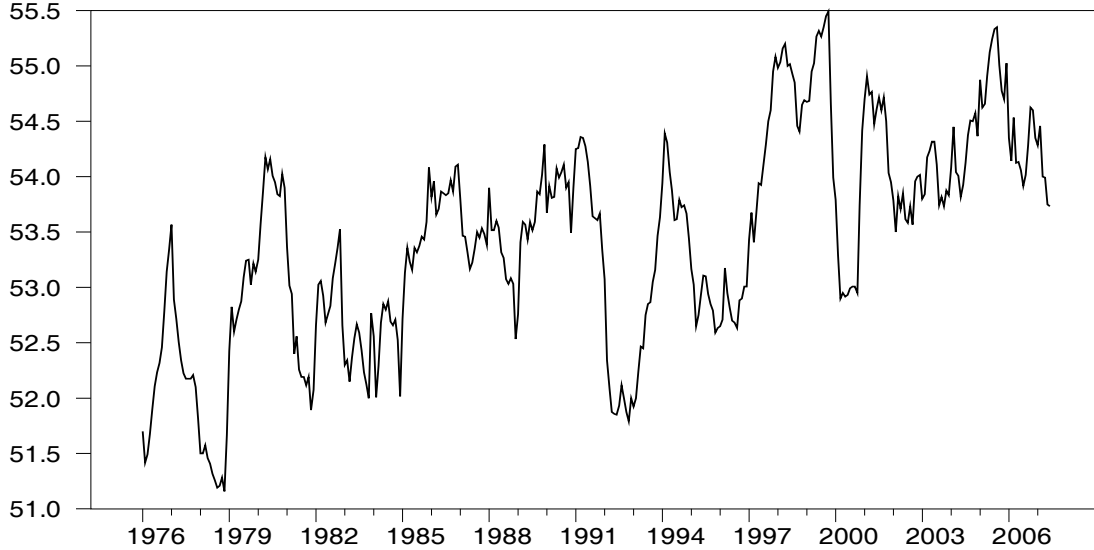
[10] The results are robust to the somewhat arbitrary choice of conditioning variables. The results presented are for the conditioning variables used in Vassalou (2003). However, the global warming risk premium estimate is nearly identical if we use lagged values of the test assets as conditioning variables, or even if we drop the conditioning variables altogether. These results are available from the authors.

Figure 2b. Global Warming Tracking Portfolio Returns, bR_t
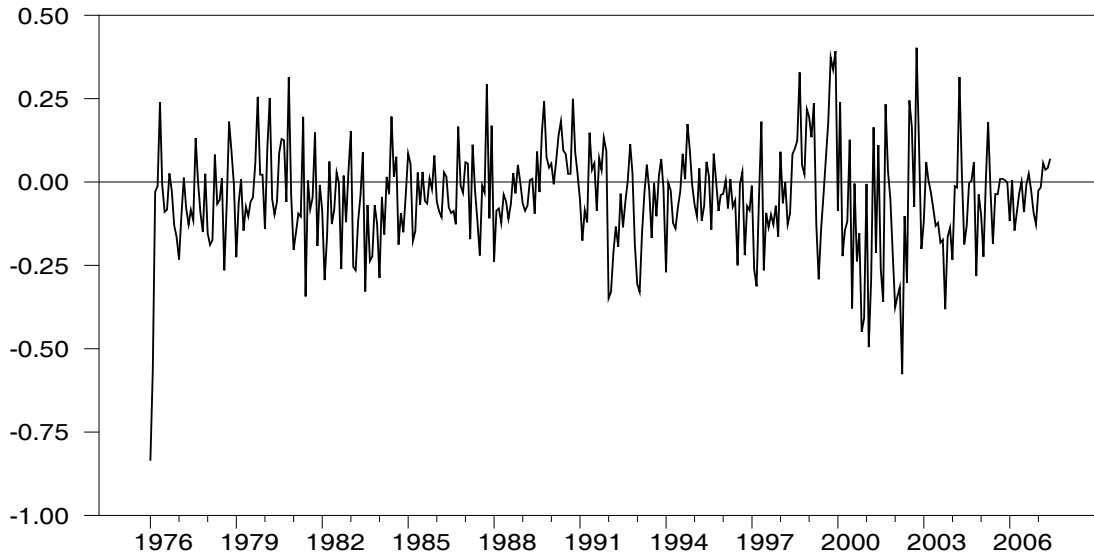
Figure 2. The average raw temperatures over the next one year, $CT_{t+12} = (\sum_{i=1}^{12} T_{t+i})/12$, are shown in Figure 2a in degrees Fahrenheit for t = 1976:1 to 2007:6. Figure 2b displays the global-warming factor series, the global-warming factor mimicking portfolio returns, for the global-warming period 1976:1 to 2007:6.

If global warming does not occur in the period before 1976, temperatures for this period ought to be irrelevant to asset pricing – mean asset returns are not driven by temperature news – and the tracking portfolio will have little power to predict future temperature. To test this conjecture, we repeat the above exercise for the IPCC pre-warming period of 1946 to 1975. The results are reported in Table 2 in the columns labeled "1946:1-1975:12". The tracking portfolio for this period has some ability to track future temperature (but significantly less than for the global warming period). However, the risk premium for this period is an insignificant -0.006 percent as anticipated.

4.5 Time Path of the Risk Premium

To obtain more information about the path of the global warming risk premium over time, we repeat the above exercise with a rolling sample. The risk premium at each time is estimated with 10 years of data to obtain meaningful estimates. Consequently the test period starts in 1956. We update estimates monthly by dropping the earliest observation and adding the latest observation. The results are displayed in Figure 3. The evidence further confirms that global warming matters for asset pricing and that its risk premium is significantly negative and apparently growing over time as is consistent with Hypotheses 1 and

2. Interestingly, the risk premium estimate shows more variability from the 1990-s onward which may reflect swings in perceptions, as the debate concerning global warming became increasingly polarized.

Figure 3. Time Path of the Global Warming Risk Premium – Rolling Estimates
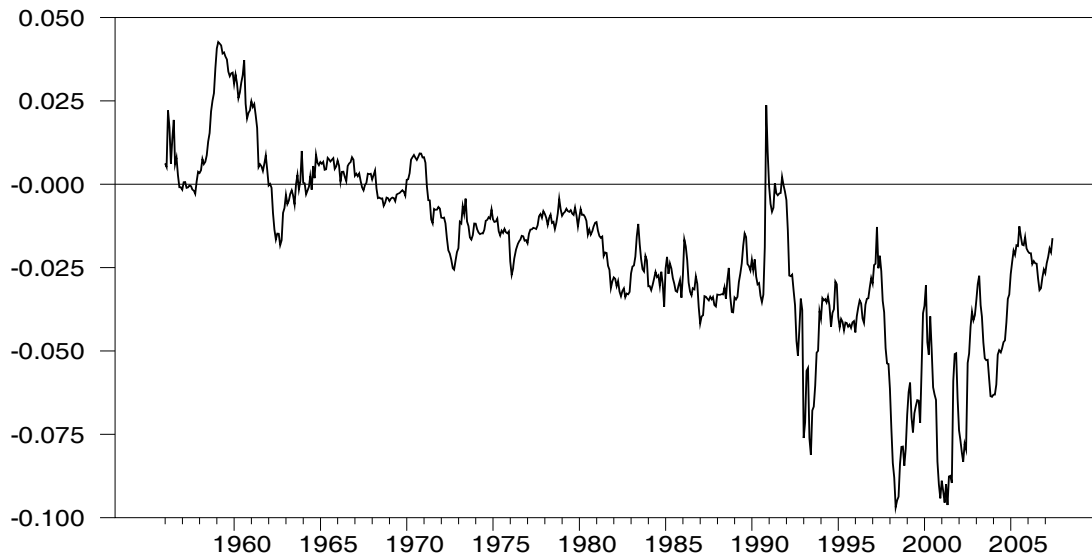
Figure 3. The risk premium is estimated for the entire 1946-2007 sample using 10 years of data for each estimate. Thus, the first period starts in 1956. We update the estimates each month by dropping the earliest observation and adding the latest observation.

5. Standard Asset Pricing Models: A Structural Approach

The tracking portfolio approach of Lamont (2001) in Section 4 estimates the risk premium of the global warming factor without specifying an equilibrium asset pricing model. In this section, we supplement these results by estimating the risk premium of global warming within a multi-factor model. This approach enables us to obtain the sensitivities to the global warming factor of particular industries, to address Hypothesis 3 and to estimate the quantitative impact of global warming on the cost of equity.

5.1. The Empirical Model

For our asset pricing specifications we take the Fama-French (1996) three-factor model and the Sharpe-Lintner CAPM. These are the most common systematic risk models. Both can be viewed as special cases of the Merton (1973) model. The global warming factor is added to these specifications as an additional factor (the only such factor in the CAPM case) affecting investment opportunities over time.

If climate-change impacts are adverse we expect to find negative loadings for typical firms or portfolios and a negative risk premium (to compensate for the additional risk the equilibrium return

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should be higher; with negative loadings this can only be achieved with a negative risk premium). The impact of global warming on the average cost of capital can naturally be measured by the product of the premium and the average loading of assets on the global-warming factor.

We use the Black, Jensen, and Scholes (1972) and Fama and MacBeth (1973) two-pass methodology – estimating factor sensitivities in the first pass, and using these to obtain risk premia in the second pass – with standard refinements: the Shanken (1992) correction to obtain errors-in-variables-robust standard errors, accounting for the fact that factor sensitivities are estimated, and the Shanken and Zhou (2007) correction to generate misspecification-robust standard errors.[11]

Lewellen, Nagel and Shanken (2009) argue that using as test assets only size–BM portfolios, as is common in the literature, can be highly misleading due to the strong factor structure of these portfolios. They propose to expand the set of test assets to include other portfolios, such as industry portfolios. Including industry portfolios also is particularly attractive for our research since the global warming literature has predictions for how different industries should be affected. Lewellen, Nagel and Shanken (2009) further argue that researchers take the predicted magnitudes of the slopes seriously, since the problems are exacerbated by the fact that empirical tests often ignore restrictions on the cross-sectional slopes. For example, the risk premium on a factor portfolio should be close to its average excess return.

We take their advice and use 55 size-BM and industry portfolios (25 size-BM portfolios and 30 industry portfolios) instead of just 25 size-BM portfolios, and force the premium on the Fama-French factors equal to their average excess returns as the risk adjustment in the second pass. That is, we employ the following CSR model

$$\bar{r}_i - (\hat{\beta}_{i,M} \bar{r}_M + \hat{\beta}_{i,SMB} \bar{r}_{SMB} + \hat{\beta}_{i,HML} \bar{r}_{HML}) = \gamma_0 + \gamma_{GW} \hat{\beta}_{i,GW} + e_i \qquad (8)$$

where the $\hat{\beta}$s are the factor loadings (jointly estimated for the four factors) from the first-pass time series regression, $\bar{r}_i$ is the mean excess return of asset I, and $\bar{r}_M$, $\bar{r}_{SMB}$ and $\bar{r}_{HML}$ are the mean excess returns of the Fama-French factors. We use the economic tracking portfolio for global warming as the global-warming factor.

5.2. Empirical Results

Since global warming represents a new systematic risk, adversely affecting investment opportunities in the economy, we expect to see that the global-warming factor is priced and that its premium is negative in the 1976 to 2007 period. The results are reported in Panel A of Table 3. The intercept in equation (8), γ_0, is not significant suggesting no model misspecification. More interestingly,

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[11] See also Kim (1995) and Jagannathan and Wang (1998).

we see that the global-warming factor indeed is priced. The premium associated with this factor, γ_{GW}, is -0.029 percent per month with an EIV-robust t-statistic of -2.86 and a misspecification-robust-statistic of -2.78, again confirming Hypothesis 1. The premium estimate is in the ballpark of its mean value reported in Table 3 which is -0.049.

Table 3. Risk Premium of the Global Warming Factor for Risk-Adjusted Returns: 1976:1-2007:6

Panel A. The risk premium on the GW factor for the sample period 1976-2007 is γ_{GW}, obtained from $\bar{r}_i - (\hat{\beta}_{i,M}\bar{r}_M + \hat{\beta}_{i,SMB}\bar{r}_{SMB} + \hat{\beta}_{i,HML}\bar{r}_{HML}) = \gamma_0 + \gamma_{GW}\hat{\beta}_{i,GW} + e_i$, where $\bar{r}_i$ is the mean excess return of asset i, the $\hat{\beta}$ s are the estimated factor loadings from the first-pass time-series regressions, and $\bar{r}_M$, $\bar{r}_{SMB}$ and $\bar{r}_{HML}$ are the mean excess returns of the Fama-French factors.

Panel B. The risk premium on the GW factor for the sample period 1976-2007 is γ_{GW}, obtained from $\bar{r}_i - (\hat{\beta}_{i,M}\bar{r}_M) = \gamma_0 + \gamma_{GW}\hat{\beta}_{i,GW} + e_i$, where $\bar{r}_i$ is the mean excess return of asset i, the $\hat{\beta}$ s are the estimated factor loadings from the first-pass time-series regressions, and $\bar{r}_M$ is the mean market excess return.

Errors-in-variables (EIV) robust standard errors are based on Shanken (1992), and misspecification (MS) robust standard errors are based on Shanken and Zhou (2007).

	Coefficient	EIV-robust t-ratio	MS-robust t-ratio
Panel A. Fama-French Risk Adjustment, 1976:1-2007:6			
γ_0	-0.038	-0.56	-0.56
γ_{GW}	-0.029	-2.86	-2.78
Panel B. CAPM Risk Adjustment, 1976:1-2007:6			
γ_0	0.120	0.94	0.93
γ_{GW}	-0.024	-2.30	-2.25

We also consider an alternative asset pricing model – the classic CAPM. We impose the restriction on the premium of the market factor. Therefore, the CSR model is:

$$\bar{r}_i - \hat{\beta}_{i,M}\bar{r}_M = \gamma_0 + \gamma_{GW}\hat{\beta}_{i,GW} + e_i \qquad (9)$$

The results are reported in Panel B of Table 3. The premium is negative and significant, confirming Hypothesis 1, though at -0.024 a bit smaller in absolute value than for the Fama-French model.

5.3. Time Path of the Risk Premium

　　To obtain more information about the path of the global warming risk premium over time, we repeat the above exercise with a rolling sample as we did for the tracking portfolio approach. The risk premium at each time is estimated with 10 years of data to obtain meaningful estimates. Consequently the test period starts in 1956. We update estimates monthly by dropping the earliest observation and adding the latest observation. The results are displayed in Figure 4. The evidence further confirms that global warming matters for asset pricing and that its risk premium is significantly negative and apparently growing over time as is consistent with Hypotheses 1 and 2. Again, the risk premium estimate shows more variability from the 1990s onward which may reflect swings in perceptions.

Figure 4. Rolling Estimates of the Global-Warming Factor Risk Premium.

Panel A. Two-Pass FF
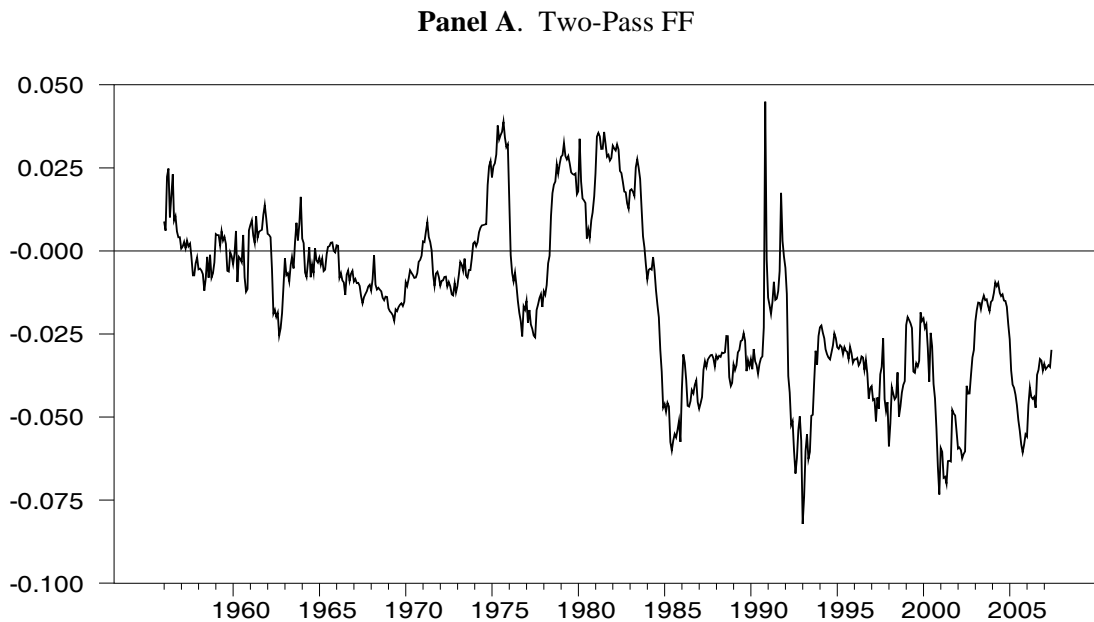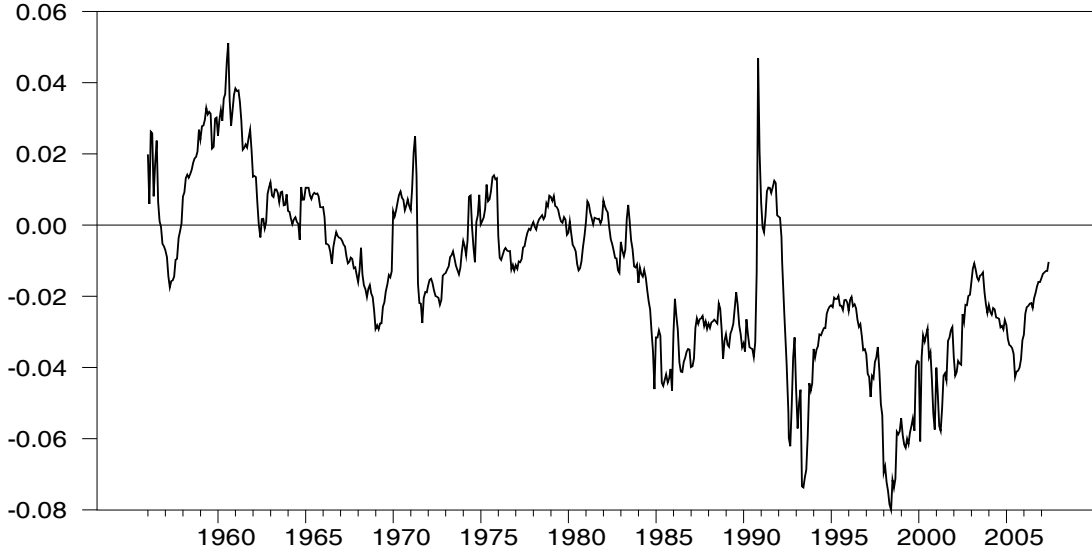
Figure 4. The risk premium is estimated for the entire 1946-2007 sample using 10 years of data for each estimate. Accordingly, the first period starts in 1956. We update the estimates each month by dropping the earliest observation and adding the latest observation.

6. Global Warming and the Cost of Capital

6.1. *Estimation*

To estimate the impact of climate change on the cost of capital, we report the factor loadings in Table 4 for the 1976 to 2007 sample period. The significant factor loadings (at the 10% level for two-sided tests) are in bold. We discuss the industry portfolio factor loadings to gauge the support for Hypothesis 3.

Table 4. Factor Loadings of the Industry Portfolios: 1976:1-2007:6

The factor loadings of the industry portfolios over the sample period 1976-2006 are inferred from:

$$r_{it} = \alpha_i + \beta_{i,M} M_t + \beta_{i,SMB} SMB_t + \beta_{i,HML} HML_t + \beta_{i,GW} GW_t + \varepsilon_{it},$$

where r_{it} is the excess return on asset i in period t, M_t, SMB_t, HML_t, GW_t are the excess returns on the market, the size, the book-to-market, and the global warming factor. The β's are the associated factor loadings, and ε_{it} is the disturbance. To save space, we do not report the associated HAC-robust (Newey-West) t-statistics. The significant factor loadings (at the 10% level of significance are in bold. The average factor loading is the unweighted average for all 55 portfolios in our tests.

Industry	α_i	$\beta_{i, M}$	$\beta_{i, SMB}$	$\beta_{i, HML}$	$\beta_{i, GW}$	Adj-R^2
Food	-0.09	0.71	0.47	0.19	**-4.73**	0.74
Beer	0.23	0.79	0.24	0.27	-3.09	0.45
Smoke	0.65	0.81	0.20	0.18	-3.05	0.19
Games	-0.36	0.97	0.88	0.24	-2.85	0.68
Books	-0.04	0.89	0.56	0.21	-3.12	0.76
Hshld	-0.35	0.90	0.68	0.16	**-5.18**	0.79
Clths	-0.41	0.92	0.69	0.21	**-6.89**	0.69
Hlth	0.52	1.04	1.39	0.21	**7.89**	0.80
Chems	-0.09	1.01	0.51	0.41	-1.69	0.80
Txtls	-0.81	0.95	0.67	0.33	**-7.62**	0.58
Cnstr	-0.32	1.04	0.74	0.36	**-5.59**	0.79
Steel	-0.40	1.23	0.87	0.76	1.89	0.69
FabPr	-0.10	1.03	0.83	0.24	-1.47	0.83
ElcEq	-0.12	1.06	1.00	0.31	1.09	0.79
Autos	-0.60	1.07	0.66	0.36	**-5.87**	0.73
Carry	-0.01	1.03	0.56	0.26	**-6.61**	0.63
Mines	-0.13	0.92	1.08	1.02	8.68	0.28
Coal	-0.37	1.05	0.63	0.87	5.17	0.22
Oil	0.02	1.04	0.61	0.69	2.51	0.35
Util	0.20	0.66	0.10	0.77	**3.97**	0.56
Telcm	0.45	1.17	1.03	0.19	**8.51**	0.70
Servs	0.39	1.14	1.19	0.02	4.75	0.82
BusEq	0.41	1.23	1.43	-0.03	5.17	0.83
Paper	-0.22	0.94	0.46	0.30	-3.52	0.80
Trans	-0.31	1.01	0.61	0.31	**-4.17**	0.76
Whlsl	-0.21	0.93	0.87	0.26	-2.03	0.80
Rtail	-0.21	0.97	0.62	0.04	**-6.80**	0.72
Meals	-0.50	0.85	0.73	0.21	**-6.57**	0.68
Fin	0.09	0.78	0.39	0.32	**-5.64**	0.80
Other	-0.08	0.97	0.77	0.22	-2.33	0.77
Average (equal)	-0.09	0.97	0.72	0.33	**-1.31**	0.67
Average (value)	0.08	0.97	0.76	0.27	**-0.31**	0.72

The literature (see IPCC, 2007, Working Group II Report *Impacts, Adaptation and Vulnerability*, Chapter 7, and Quiggin and Horowitz, 2003) suggests that the most vulnerable industries are Agriculture and Forestry, Transportation, Retail, Commercial Services, Tourism, Insurance, those industries dependent on climate-sensitive inputs (such as Food Processing), and industries with long-lived capital assets. The results in Table 7 seem generally consistent with this classification, confirming Hypothesis 3. In all, 14 out of 30 industry portfolios have statistically significant loadings on the global-warming factor,

even after we control for the effects of the Fama-French factors. They include Food, Meals, Finance, Transportation, Retail, and Construction.

All of the significant loadings on the global-warming factor are negative except for the Utility, Telecommunications, and Health industries. The utility industry has a small demand elasticity, and therefore may provide a good hedge against negative supply shocks. The telecommunications and health industries appear also to have small demand elasticities. The (equal-weighted) average loading on the GW factor is significant and equal to -1.31. To obtain the average cost of equity capital, however, we calculate the value-weighted average loading by weighting each loading by the market value of the industry. The resulting weighted average cost of equity capital is a substantially smaller -0.31.

The global warming risk premium is -0.029% per month based on the two-pass regression for the Fama-French risk factors. Taken together with the value-weighted average GW loading of -0.31, the results reveal that the GW factor increases the average cost of capital by 0.009% per month or *0.11%* per year. The question we address next is what this number implies about the cost of global warming and how it relates to previous studies providing global warming cost estimates.

A convenient means of accounting for the costs of global warming is to use the Gordon growth model approximation arising when we equate asset prices with the expected net present value of future dividends, and proxy the latter by setting the dynamic paths of dividends, dividend growth, and costs of capital equal to their averages. Aggregate stock market values can then be expressed as $P = D/(R - G)$, in which *P* is the current stock market price index, *D* the end-of-period expected dividends (considered a constant proportion of GDP), *G* the average anticipated growth rate of dividends, and *R* is the average cost of capital.

6.2. Implications

We can then draw the following conclusions based on the existing literature and our own results:

(1)   The estimated cost of global warming in terms of *permanent* future decreases in GDP, as emphasized by previous literature, vary from around 0.2% to 1.0% (Stern, 2007) and below 1% (IPCC, 2007) to 2.0% to 3.5% per 1 degree Celsius increase in temperature (Choinière and Horowitz, 2006) and a maximum of 3.75% (Heal and Kriström, 2002). Even though these estimates deal with permanent changes in GDP the *present value* of the cost, assuming that dividends remain a constant proportion of GDP and even if the changes occur without delay, is simply the equivalent percent change in stock market value: the Gordon growth equation implies that $\% \Delta P = \% \Delta D$.

(2)   Henry (2003) finds an approximate one-to-one relationship between the cost of capital and GDP *growth*. This is consistent with the Gordon growth perspective in which the impact of a change in the cost of capital is equivalent to the impact of an opposite change in the growth rate of dividends or

output: $\%\Delta P / \Delta R = -\%\Delta P / \Delta G$.   Accordingly, the stock market wealth impact of our 0.11 percent increase in the cost of capital is equivalent to that of a 0.11 percent reduction in the growth rate of dividends or output. Since the IPCC cost of limiting the long-term temperature rise is a 0.12 percent reduction in annual GDP growth, the impact of global warming on the cost of capital alone is of similar magnitude as the total policy cost, which allows room to contemplate more aggressive climate-change mitigation policies.

(3)   The Gordon growth approximation also implies that $\%\Delta P = -(P / D)\Delta R$. If we set *P/D* (the price-dividend ratio) equal to 38, which is its average value over the global warming period, since 1976 (see Robert Shiller's website) then the present value of the cost of global warming is 38 x 0.11% = 4.18%. This negative impact alone is close to the 4.56 percent cost of reducing global warming based on the IPCC estimate.

6.3. Perspectives

To put our estimate of a 4.18 percent loss due to global warming in the perspective of previous estimates, consider the following:

First, the literature has considered mainly the specific present value costs of permanent future losses in GDP due to abrupt climate change, and, more recently, the costs of losses in GDP related to extreme weather due to gradual climate changes. However, the uncertainty about temperatures, extreme weather, and associated regulation adds substantially to the overall costs and shows up in the higher cost of capital which previous studies have ignored in this context. Thus our result amounts to adding an additional present value cost of global warming of larger magnitude to previously identified costs.

Second, our estimate of a 4.18% loss presumes that the change in the cost of capital is permanent. Our rolling regression results for the risk premium shows how dangerous this assumption is – clearly the risk premium changes substantially over time. However, we have taken conservatively the *average* risk premium since the start of the global warming period, which Figures 3 and 4 show is smaller in absolute value than the risk premium has been over the last ten years. (Note, though, that the CAPM and the tracking portfolio results suggest a recent decline in the risk premium). While it is certainly possible that the cost of capital attributable to global warming may decrease again over time, it may also increase over time, and there is no reason to assume that uncertainty about climate change is diminishing in the near future.

Third, an approximate confidence interval of two standard deviations around our monthly risk premium estimate would provide a range from 0.009% to 0.049% for the GW risk premium. At the lower bound the cost estimate would be an annualized 1.27%, at the upper bound an annualized 6.93%. Thus, estimation uncertainty is substantial.

Fourth, it is not clear how representative the United States stock market values are of the world. Developed economies experience higher losses due to the adjustment costs of capital and so the costs for the United States may overestimate those for the world. A further implicit assumption is that the stock market losses are representative for losses in the overall economy. It is possible for instance that certain sectors of the economy are over or under represented in the stock market or that there are distribution effects within a sector. For instance, farmers may suffer from global warming but this need not lower profit margins in the food industry.

Fifth, our estimates do not take into consideration time variation in the average value-weighted loadings on the GW factor. Industries with larger increases in the cost of capital may shrink over time as investment in these industry falls, causing the value-weighted loadings to move closer to zero. On the other hand, such reduction in investment lowers growth, an indirect effect that we have not yet incorporated in the cost calculation.

6.4. Uncertainty about regulation

One potential explanation for the sensitivity of particular industries to our global warming measure is that the global warming indicator has little intrinsic economic importance (either because it is a statistical illusion, has only minor economic impact, or is too remote to affect current present values) but that markets fear the political pressures arising from common perceptions of a global warming threat that may lead to untoward regulation hurting business profits. This "untoward regulation" line of reasoning implies that those industries which are most vulnerable to regulation designed to reduce global warming would be the most sensitive to the global warming factor. A prospective regulatory impact generally entails rationing or taxation of carbon-dioxide emissions. Hence the prediction is that industries that are the most sensitive to the global warming factor are those industries that have the highest share of carbon dioxide emissions.

Schipper (2006, pp. 17-19) provides data on carbon-dioxide emissions in U.S. manufacturing. Manufacturing accounts for around 84 percent of energy-related carbon dioxide emissions. The Petroleum (Oil), Chemicals, and Primary Metals (mostly Steel) industries have the highest carbon dioxide emissions, together generating more than half of these emissions. However, according to Table 4 *these industries have either positive or insignificant sensitivities to the global warming factor*. Furthermore, many of the industries in Table 4 with the most significant negative exposures to the global warming factor are non-manufacturing industries such as Finance, Retail, and Meals, with obviously low carbon-dioxide emissions. These observations do not support the "untoward regulation" explanation.

7. Conclusion

The severity of impact and even the existence of global warming are heavily debated. On one end of the debate are the "environmentalists" who care deeply about the negative long-run impact of climate change and may be tempted to under appreciate the economic sacrifices required to combat global warming; on the other end are the "industrialists" who may be owners of capital and overly occupied with the costs necessary to implement policies of fighting global warming. The controversy makes it difficult to obtain an unbiased measure of even the perceived costs of global warming. Financial markets may be helpful in uncovering true perceptions. When investing in financial assets, individuals – irrespective of their background or political convictions – have an incentive not to "put their money where their mouth is" but to put their money where their mind is. Asset prices provide objective measures of perceived value. We attempt to exploit the information embedded in asset price reactions to news about global warming to infer an objective measure of perceived costs of global warming.

We focus on gradual temperature change, which is motivated by the recent emphasis of Stern (2007) and IPCC (2007) on the ongoing costs of extreme weather events that stem from gradual warming.[12] Our approach ties into the gradual warming perspective and stresses the higher cost of capital that arises from uncertainty about the extent of gradual warming and the increasing prevalence of extreme weather events. The costs of global warming that we derive, therefore, are a complement to the costs found in the earlier work and should be added to previous cost estimates to obtain a more comprehensive cost total.

While we may draw inferences about the broad question of what financial markets in general can tell us about global warming, we obtain a more reliable answer to a narrower question: how do U.S. equity markets react to news about average U.S. temperatures? If we work in the context of (*i*) the Merton (1973) asset pricing model and (*ii*) presume that the IPCC (2007) is justified in marking the post-1976 period as one of global warming, then we hypothesize that a significant risk premium exists on a global warming factor, which is rising in the post-1976 period, and that loadings at the industry level on this factor are generally negative and more so for industries that are considered to be more sensitive to global warming.

We are able to confirm the hypotheses and infer, conservatively taking the average risk premium for the post-1976 period, that the average cost of capital is 0.11 percentage points higher on an annual basis due to global warming. Thus, markets expect that due to the uncertainty, the costs of adjustment, and the increased incidence of extreme-weather events, each caused by global warming, potential projects will on average have a 0.11 percentage points lower return. The implied costs of global warming amount to a point estimate of a 4.18 percent loss in value – larger than, and adding to, most previous estimates.

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[12] In analogy to the terminology used in evoluationary biology distinguishing between the standard gradual Darwinian perspective and Gould's punctuated equilibrium theory of abrupt evolutionary changes, we may refer to the distinction here as global warming by "creeps" and global warming by "jerks".

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