Department of Finance
Faculty of Business and Economics

Working Paper Series

Carbon Dioxide and Asset Pricing: Evidence from International Stock Markets

Zhuo Chen, Jinyu Liu, Andrea Lu

Working Paper No. 11/20

Carbon Dioxide and Asset Pricing: Evidence from International Stock Markets

Zhuo Chen* Jinyu Liu† Andrea Lu‡

Abstract

We use carbon dioxide (CO_2) emissions growth to measure consumption risk within a consumption-based capital asset pricing model (CCAPM) framework. Given the comprehensive worldwide coverage of CO_2 emissions, this measure allows us to use the full history of stock market data in the United States, Europe, the world, and fifteen international markets. For the United States (Europe/the world), we are able to explain the observed equity market premium with a relative risk aversion (RRA) of 6 (10/12), which is less than half the size of that estimated using the canonical expenditures-based consumption growth measure. The average estimated RRA across fifteen other international markets is 7. We also find evidence that the growth of CO_2 emissions is a priced risk factor that captures the cross section of stock portfolio returns.

JEL Classification: G12, Q43
Keywords: International Asset Pricing, Consumption-Based Capital Asset Pricing Model, Carbon Dioxide Emissions

*PBC School of Finance, Tsinghua University. Email: chenzh@pbcsf.tsinghua.edu.cn. Tel: +86-10-62781370.

†School of Finance, University of International Business and Economics. Email: jinyu.liu@uibe.edu.cn.

‡Department of Finance, University of Melbourne. Email: andrea.lu@unimelb.edu.au. Tel: +61-3-83443326. The authors thank Torben Andersen, Snehal Banerjee, Jules van Binsbergen, Jason Chen, Anna Cieslak, Zhi Da, Paul Gao, Ravi Jagannathan, Robert Korajczyk, Adair Morse, Tyler Muir, Dimitris Papanikolaou, Jonathan Parker, Annette Vissing-Jorgensen, Jianfeng Yu, and seminar participants at the 25th Australasian Finance and Banking Conference, the Midwest Finance Association 2013 Annual Meeting, and the Kellogg finance bag lunch for helpful comments and discussions.

A fundamental question in asset pricing is how macroeconomic risks, such as consumption risk, relate to the pricing of financial assets in the time series and the cross section. In the consumption-based capital asset pricing model (CCAPM), introduced by Lucas (1978) and Breeden (1979), investors require risk compensation for holding assets that comove with consumption growth. In that model, cross-sectional variation in expected asset returns is driven by the covariances between assets' returns and households' consumption growth. Despite its theoretical simplicity, many studies have shown that the CCAPM does not fit the empirical data well. An extremely high level of relative risk aversion is required to generate the observed risk premium when per capita household expenditures on nondurable goods and services are used to measure households' consumption (Mehra and Prescott 1985); the model-implied risk-free rate is too large (Weil 1989); and the model poorly prices the cross section of stock returns.

Researchers have done a tremendous amount of work to justify the CCAPM and solve the "equity premium puzzle". Theorists have developed complicated representative consumer utility functions, including the separation of the elasticity of intertemporal substitution and risk aversion (Epstein and Zin 1989; Weil 1989), the slow-moving long-run consumption risk component proposed by Bansal and Yaron (2004), and the habit persistence model (Campbell and Cochrane 1999). On the empirical side, researchers have tried to capture consumption risk across many different perspectives, including the ultimate consumption risk over a longer horizon (Parker and Julliard 2005), the role of stock market participants' long-run consumption risk (Malloy, Moskowitz, and Vissing-Jorgensen 2009), and the timing effect of measuring households' consumption growth (Jagannathan and Wang 2007). In addition, some researchers use creative alternatives to measure consumption, which yields higher volatility for consumption growth (Da and Yun 2015; Savov 2011; Chen and Lu 2017).

Our rationale for using carbon dioxide (CO_2) as a proxy for households' consumption is similar to that of Chen and Lu (2017). Today, human life is heavily dependent on energy consumption, almost all of which involves CO_2 emissions. Take the simple example of preparing a home-cooked meal. CO_2 emissions are generated in various ways: electricity for lighting and refrigerating; gas for cooking and heating; and gasoline for driving to the store to buy groceries, all of which follow from the supply chain logistics involved in getting groceries into the hands of consumers, a process also heavily dependent on energy consumption. Changes in CO_2 emissions should be informative about the growth of aggregate household consumption. Meanwhile, CO_2 emissions growth has a high correlation with the stock market return and is more volatile than the canonical expenditures-based consumption growth measure. For example, U.S. CO_2 emission growth has a correlation of 42% with the U.S. market return, and emissions growth itself has a standard deviation of 7.5%, which is three times more volatile than the per capita growth of personal expenditures on nondurable goods and services from the National Income and Product Accounts (NIPA). Both features contribute to CO_2 emissions' ability in explaining the time-series and cross-sectional variation in stock returns under the standard CCAPM framework. The difference between our study and that of Chen and Lu (2017) is that to fully utilize the long history and wide cross section of the international CO_2 emissions data set, we directly use CO_2 emissions as a proxy for households' consumption under the CCAPM framework with a standard constant relative risk aversion (CRRA) utility model without distinguishing between the different types of consumption and/or specifying more complex preference functions. As a result, we are able to utilize the full sample of stock market data in a wide range of international markets: we test the CCAPM using a long sample of over 140 years in the United States and in fifteen other international markets with the majority samples spanning over 100 years. The comprehensive coverage in both length and width facilitates better empirical insights on the validity of the CCAM and allows us to investigate the implications of CCAPM on asset prices in a more accurate fashion.

Compared with traditional personal expenditures and other alternative consumption measures, our CO_2-emissions-based consumption measure has several advantages that lead to more accurate and comprehensive empirical results. First, CO_2 emissions capture a broad range of energy consumption, including, but not limited to, electricity consumption like in Da and Yun (2015). Fossil fuels, the usage of which generates a significant amount of CO_2, play an important role in electricity generation in the United States. In 2018, around 64% of the electrical energy generated used fossil fuels, an amount that directly generated CO_2. The time series of CO_2 emissions should not only incorporate movements in electricity consumption but also contain more information about other types of energy consumption that underly households' consumption activities.

Second, CO_2 emissions capture the transportation component of households' consumption. Households have been evolving toward a lifestyle with more travel and leisure activities. Households are also spending more on services that can involve an intensive use of transportation. Expenditures related to transportation, however, are difficult to capture by measures like, for example, garbage generation (Savov 2011) or electricity usage (Da and Yun 2015), because these activities may not generate much garbage or use much electricity. Our data directly include emissions from the consumption of petroleum used in transportation. They can therefore capture changes in transportation-related household consumption.

Third, CO_2 emissions account for the housing component of households' consumption. Households spend significant amounts on housing. According to the U.S. Department of Labor Statistics' Consumer Expenditures Survey, in 1984, more than 16% of households' consumption expenditures goes to shelter, which includes property rental expenses and/or mortgage payments. This number has increased to almost 20% in 2018. CO_2 emissions can indirectly address this issue in the way that larger houses typically have more household activities that induce more emissions. Our CO_2 emissions also further capture consumptions related to housing by including CO_2 emissions from cement production and emissions involved with the production and transportation of housing construction. Housing-related expenditures have been found to be closely related to the growth rate of new construction and thus the consumption of cement. Cement manufacturing processes release CO_2 when calcium carbonate is heated, thereby generating lime and CO_2 in the process. The production of other building materials and the transportation of these materials are petroleum based, meaning they are made from crude oil, a process that induces CO_2 emissions. By including these elements, we can better capture movement in housing-related consumption expenditures using CO_2 emissions.

One potential limitation of our CO_2 emission measure is that a portion of CO_2 emissions may arise from energy used in the production of the nonenergy commodities other than the direct consumption of energy commodities. This would be a concern if the first is more important in driving the changes in CO_2 emissions and the correlation between the two is weak. We would ideally want to isolate emissions associated with consumption from the data. Unfortunately, these data do not allow us to do so. However, the research on emissions has offered guidance indicating that this potential limitation should not be a major concern. Munksgaard, Pedersen, and Wien (2000) find that the consumption of nonenergy commodities accounts for almost as much of CO_2 emissions as the consumption of energy commodities. They conclude that the overall growth in household consumption is the main driving force behind growth in CO_2 emissions. Based on this finding, although we recognize the difference between production and consumption, we believe CO_2 is still a relatively clean empirical proxy for household consumption that can closely track the true consumption process.

Our empirical findings add to the CCAPM literature with some important findings. First, the CO_2-emissions-based consumption growth measure helps to resolve the joint equity risk premium and the implied risk-free rate puzzles observed in the U.S. stock market. Using the annual growth rate of CO_2 emissions as a proxy for consumption growth, we achieve a very reasonable estimated relative risk aversion coefficient of 6 and a small implied real risk-free rate of 0.63% in the United States under the CCAPM framework with CRRA utility over the full sample period of 1872 to 2015. The RRA estimate is less than half of those estimated using the traditional expenditures-based counterparts in terms of magnitude. We also find a similar magnitude of improvement in European and the world markets. The CO_2-emissions-based measure also delivers an average RRA of 6.58 in fifteen countries over a long sample of over 100 years. Second, our results offer a more comprehensive understanding of the performance of our CO_2 emissions measure in measuring consumption across a long sample horizon. Using pre- and post-oil-crisis subsample analyses, we find that, even though our measure of CO_2 emissions growth captures consumption risk in a simple CCAPM framework, the measure is stronger in the pre-oil-crisis sample than in the post-oil-crisis sample, and its improvement over the canonical expenditures-based consumption growth measure is persistently evident over time. Third, CO_2-emissions-based consumption growth contributes to explaining the cross section of stock returns. Specifically, it explains the returns of the U.S. stock portfolios with a positive and significant price of risk and the smallest pricing error and root-mean-square error (RMSE) among all models considered, including those controlling for the market factor and the expenditures-based consumption growth measure.

The rest of the paper is organized as follows. Section 1 provides a description of the data. It also details the construction of the annual per capita growth rate of CO_2 emissions. We reinvestigate the equity premium puzzles in the United States and in international stock markets in Section 2 using the CO_2 emissions-based measure. In Section 3, we implement cross-sectional asset pricing tests using CO_2 as an alternative measure of consumption. Section 4 concludes.

1. Data

In this paper, we use CO_2 emissions to proxy for consumption. The CO_2 emissions data we use are commonly used in studies [CG2]of CO_2 emissions and have been constructed following the procedures discussed in Marland and Rotty (1984) and Boden et al. (1995). The data are sourced from the Oak Ridge National Laboratory (ORNL) for the sample prior to 2014 and from the Global Carbon Project for 2015–2016. Emissions data from these two sources are constructed using the same raw data and are based on the same methodology. The change merely reflects a change of its host. These data provide CO_2 emissions from aggregate fossil fuel consumption and cement manufacture at an annual frequency over 200 countries worldwide. Quantities of CO_2 emissions are measured in the standard unit of 1,000 metric tons of carbon. The time series of CO_2 emissions is constructed by applying CO_2 emissions conversion coefficients to historical records of energy consumption series.[1] Specifically, CO_2 emissions of fuel type i are estimated as the product of three terms: quantity consumed of fuel type i, the carbon content of fuel type i, and the fraction of the carbon content that is oxidized.[2] Quantities of fuel consumption are controlled for by changes in the form of fuel, fuel imports and exports, and changes in fuel stocks. They provide good estimates for the amount of fuel that generate CO_2 emissions as the result of people's consumption.

One key advantage of the CO_2 data set we have used, besides it being the commonly used data set in studies of CO_2 emissions, is that it provides an exceptionally long record of CO_2 emissions for all developed countries and most developing countries tracing back to 1751. The coverage, in both length and breadth, exceeds that of available stock returns data.

[1] Andres et al. (1999) provide details on the contents and processing of the historical energy statistics from 1800 to 1949. The 1950 to 2016 CO_2 emission estimates are derived from energy statistics published by the United Nations. The U.S. Bureau of Mines compiles the cement manufacturing data.

[2] In their estimation methodology, Marland and Rotty (1984) assume the fraction of carbon content and the fraction oxidized to be constant over time. Although the carbon content of fuel has not varied considerably since the nineteenth century, the components of the fraction oxidized do vary because of improvements in combustion efficiencies, as well as nonfuel usage, including appreciable uses in plastics and lubricants. Both nonfuel uses and combustion efficiencies have increased over time. However, the two effects counter one another, and, therefore, we are able to keep the fraction oxidized constant.

The long and comprehensive coverage enables us to exploit the full sample of stock market data in a wider range of countries, in addition to looking at some key regions, including the United States, Europe, and the world. A consumption measure constructed based on the CO_2 emissions thus would allow us to investigate the long-run performance of the CCAPM and the performance of the CCAPM in international markets.

We use CO_2 emissions generated from the combustion of solid fuel and liquid fuel net emissions from gas flaring to proxy for households' consumption. Solid fuel refers to various types of solid material used to produce energy like charcoal and coal. Liquid fuel includes crude petroleum, natural gas liquid, and liquefied petroleum gas (LPG). Gas fuel refers to natural gas. We purposely exclude emissions from cement production and gas flaring from our CO_2 emissions measurement because of their lack of relevance in capturing consumption. Emissions from cement production captures the amount of CO_2 released when calcium carbonate is heated during the manufacturing of cement, and emissions from gas flaring are generated when natural gas is flared at oil fields in some remote locations because of the lack of markets and infrastructure. Neither are directly associated with households' consumption.[3]

Following Campbell (1999) and Savov (2011), we adopt the standard approach in the CCAPM literature to compute CO_2 emissions growth and match it with the stock return data using the beginning-of-period convention. Specifically, the growth rate of CO_2 emissions in year t is calculated using the CO_2 emissions from year $t+1$ and t and then matched with the stock returns of year t. We adjust emissions by population whenever possible. The population data for the United States is from the U.S. Census Bureau. Population estimates are always reported on the first of July each year, so we use the average of the population

[3] In fact, the decision of whether or not to include emissions from gas flaring in our measure makes little difference. Emissions from gas flaring on average account for less than 0.5% of total emissions over the full sample and 1% at its peak in the 1970s. The correlation between total emissions and the total net of gas flaring emissions is over 99.99%.

in year t and year $t-1$ as the population in year t in the calculation of per capita CO_2 emissions. Population data for the rest of the world are only available from the World Bank after 1950. Therefore, we replace the per capita emissions with the raw aggregate emissions data in calculating emissions growth for Europe, the world, and other countries, excluding the United States, in the pre-1950 sample. In fact, because of the slow-moving nature of population growth, especially in the list of (mostly developed) countries we consider, the application of population adjustment has little effect on the movement of the computed emissions growth series: we find that the growth series computed using emissions with and without population adjustment has a correlation of over 99%.

Too fully benefit from the length and breadth of CO_2 emissions data, we obtain stock returns data from multiple sources to cover a wide range of countries and regions over a long sample. We use a country- and region-level stock market index and portfolios to test the assets in our sample. The U.S. stock market index is based on the value-weighted index available from the Center for Research in Security Prices for the period of 1930–2008 extended backward for the 1872–1929 period using data from Robert Shiller's website. For Europe, the return of the stock market index is constructed by merging the Global Financial Database's Developed World Europe Return index from 1907 to 1985 with the MSCI Europe index post-1986 (both measured in USD). The stock market return for the world comes from Thomson Reuter's Credit Suisse Global Investment Returns Yearbook. After matching CO_2 emissions growth with the stock market returns data, the longest sample for the United States, the Europe, and the world is 1872–2015, 1872–2015, and 1907–2015, respectively. For the stock portfolios, we use the Fama-French 25 size and book-to-market portfolio constructed for the United States, the Europe, and the world, respectively. These are downloaded from Kenneth French's website, and we subtract the risk-free rate of each region to calculate the excess returns. The sample period is 1929–2015 for the United States and 1991–2015 for the Europe and the world. Annual excess stock market returns for a list of sixteen other countries are obtained from the Global Financial Database. This list of countries includes Australia, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Netherlands, New Zealand, Spain, Sweden, Switzerland, and United Kingdom. Because the CO_2 emissions data are always longer than the length of the stock returns data available, the final samples used in this study are defined by the length of the stock returns sample, which varies by country, with the earliest one starting from 1872.

[Insert Table 1 here]

Panel A of Table 1 presents the summary statistics of the annual per capital growth of total CO_2 emissions. The per capita growth of the total CO_2 emissions has a sample mean of 1.40%, 1.42%, and 2.49% per year for the United States, Europe, and world, respectively, over the full sample. The corresponding standard deviations in the same period are 7.48%, 6.80%, and 5.29%. The growth of total CO_2 emissions has a high correlation with the excess return market portfolio for the United States (42.05%) and the (39.73%) but less so for the Europe (18.44%). This comovement can be seen in Figure 1, which plots the time series of CO_2 emissions growth and the market real excess return for these three regions. CO_2 emissions growth clearly comoves with the stock market returns in all three regions. Comovement is particularly evident in the pre-oil-crisis period, where CO_2 picks up most of the large movements in the stock market, especially on the downside, and is stronger in the United States and the world but less so in Europe. In Panel A, where we also include periods of U.S. recession, we can see that almost all recessions in the United States start with a sharp drop in both the growth rate of CO_2 and the associated stock market return. These observations support CO_2 emissions growth as a reasonable proxy for consumption risk in explaining the cross-sectional and time-series variation in stock returns. We also observe that the growth of CO_2 emissions tends to become smoother over the later part of the sample, particularly in the post-oil-crisis sample: the mean emissions growth is much lower for all three regions and so are the standard deviations. Although the correlation with market returns remains high for the United States and the world, CO_2 emissions growth no longer responds to the large movement in stock market as sensitively as in the earlier sample, indicating that the ability of our measure of CO_2 emissions to proxy for consumption can be regionally and sample dependent.

[Insert Figure 1 here]

2. Estimating the CCAPM parameters

Despite its profound theoretical influence, the CCAPM has encountered problems in empirical testing when using the growth rate of the NIPA personal consumption expenditures for nondurables goods and services. Specifically, there are two commonly well-documented puzzles: first, an extremely high level of risk aversion is required to rationalize the observed equity risk premium, and, second, the model-implied risk-free rate is too large relative to its observed value. Under standard model assumptions, these observations can be interpreted as the result of the NIPA personal consumption expenditures growth being too smooth to capture the true risk associated with consumption growth. CO_2 emissions are closely related with households' consumption, and the growth of CO_2 emissions is more volatile, while correlated with the market returns, so we believe our CO_2-emissions-based consumption measure can capture households' underlying consumption risk more adequately. In this section, we empirically investigate whether our CO_2-emissions-based consumption growth measure helps to justify the high risk premia observed in the stock market and yields a more reasonable model-implied risk-free rate.

We conduct our tests under the standard CCAPM assumptions of Lucas (1978) and Breeden (1979). Key assumptions include (1) a two-period model; (2) a complete market; and (3) a power utility function. Under these standard assumptions, the Euler equation that prices any asset is expressed as

$$E_t[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}R^e_{t+1}] = 0, \tag{1}$$

where β is the subjective discount factor; C_t and C_{t+1} are the representative agent's consumption in period t and $t+1$; γ is the coefficient of relative risk aversion in the representative agent's power utility function; and R^e is the excess return of any asset in the market. We fix the subjective discount factor, β, to be 0.95 following many studies (see Hansen and Singleton (1982); Savov (2011); Da and Yun (2015); Chen and Lu (2017), among others).[4] Given the observed market excess return and CO_2-emissions-based consumption growth, we estimate the coefficient of relative risk aversion γ using the generalized method of moments (GMM), where the Euler equation expressed in Equation (1) is used as the moment condition.

2.1 U.S. evidence

We estimate the relative risk aversion coefficient using the U.S. market portfolio as the test asset and U.S. per capita CO_2 emissions as a proxy for consumption. The baseline results estimated over the full sample of 1872 to 2015 are presented in the first column of Table 2, Panel A. The annual per capita growth rate of CO_2 emissions yields a relative risk aversion coefficient of 6.24, which is realistic from an economic perspective. The model-implied risk-free rate is 0.63% per year, in real terms, which is lower than its empirical counterpart over the same sample period. However, it poses less of a puzzle compared with its counterpart implied by the canonical expenditures-based estimate, which we present in later results. In addition, the pricing error of the estimation is zero to four decimal places, indicating that the just-identified model is validated using the CO_2 emissions growth data. These estimated CCAPM parameters indicate that the United States' total CO_2 emissions per capita growth

[4] The model's performance is not qualitatively affected by the choice of β. The results are available from the authors on request.

can explain the equity premium in the U.S. market portfolio over a long horizon with an RRA and a model-implied risk-free rate at an economically sensible magnitude.

Alleviation the CCAPM's associated puzzles is effective when we the CO_2-emission-based estimates with those estimated using the canonical expenditures-based measure, which is calculated as the growth rate of real per capita personal consumption expenditures on nondurable goods and services. In the first two columns of Table 2, Panel B, we compare these estimates over the sample of 1929–2015, which is the longest sample that can be obtained subject to the availability of the expenditures-based measure. Using CO_2 emissions growth as a proxy for consumption risk produces a lower estimated RRA of 6.75, which is almost half of the RRA of 16.24 produced using the expenditures-based measure. The model-implied risk-free rate using the CO_2 measure is negative at -4.18% over this sample; however, in terms of absolute magnitude, it is still more reasonable compared with the 31.72% implied using the expenditures-based measure.

[Insert Table 2 here]

We further analyze the time variation in the performance of CO_2 emissions in proxying household consumption in solving the equity risk premium puzzles. We do so by estimating and comparing the estimated relative risk aversion coefficient and the model-implied risk-free rate over two subsamples. We use the oil crisis in 1973–1974 to classify our sample into pre-oil-crisis and post-oil-crisis subsamples. We estimate the Euler equation separately in the pre-oil-crisis period of 1872–1973 and the post-oil-crisis period of 1974–2015. We choose the oil crisis as the subsample classification, because the oil crisis was one of the main driving forces that lead to global public awareness of energy conservation and improvements in energy efficiency. In addition, the 1970s mark the beginning of decades of significant increases in trade inflow into many countries, including the United States. Therefore, the relation between CO_2 emissions growth and the true underlying households' consumption risk could vary between our subsamples because of changes in the quantity of goods (and services) being consumed in one country but manufactured (thus CO_2 emissions) in other countries. The CCAPM parameters estimated using CO_2 emissions growth for the two subsample periods are presented in columns 2 to 3 in Table 2, Panel A. The per capita growth rate of CO_2 emissions consistently delivers economically reasonable estimates for the relative risk aversion at zero pricing errors: the estimated RRA is 5.27 over the 1872–1973 period and 14.39 for the 1974–2015 period. The model-implied real risk-free rates are 4.32% and -13.14%, respectively, for the two subsamples. It is true that CO_2 emissions growth does a better job matching the CCAPM to the market excess returns in the pre-oil-crisis period than in the post-crisis period. This change in performance suggests that global awareness, improvements in energy efficiency, and offshore production of goods do jointly affect the ability of our CO_2 emissions measure to capture households' consumption. The weaker performance of the CO_2 emissions measure in accessing aggregate consumption risk in the later sample is in some way consistent with the finding in Chen and Lu (2017). In that paper, the authors illustrate that the time-varying utilization of durable goods is important in explaining assets' risk premium under an CCAPM framework with Epstein-Zin preferences, and they find that CO2CO_2 emissions can be useful in empirically measure this time-varying utilization of durable goods in the post-1970 period, when households' holdings of durable goods stock shift toward energy-dependent durable goods. In other words, whereas CO_2 emissions are related to households' consumption, the component of households' consumption being captured changes over time and thus affects the ability of CO_2 emissions to serve as a proxy for consumption risk in a simple CCAPM framework of which there is no distinction between different types of consumption. The complexity of households' consumption profile also requires a more sophisticated CCAPM framework to understand its relation with asset prices.

[Insert Figure 2 here]

Nevertheless, CO_2 emissions growth still outperforms the expenditures-based consumption growth measure by far in terms of delivering more sensible CCAPM parameter estimates. The expenditures-based consumption growth measure gives a very high RRA estimate of 43.62 and an implied risk-free rate of 92.43% in the post-oil-crisis period. The outperformance of the CO_2-emissions-based measure is prevalent in all subsamples. Figure 2, Panel A, graphically illustrates this point by plotting the RRAs estimated using CO_2 emissions growth and the expenditures-based consumption growth measure over a rolling window of 50 years. We see that the CO_2-emissions-based measure consistently yields a RRA of under 15 right up until the early 1990s. The CO_2-emissions-based RRA has never exceeded 40, whereas the expenditures-based RRA reaches almost 100 in the same period. Overall, the CO_2-emissions-based RRA is always less than half of that estimated using the expenditures-based measure in terms of magnitude.

2.2 Europe and the world evidence

We then consider whether CO_2 emissions growth can act as proxy for consumption growth in the CCAPM framework using the European and world data. Before testing the data, because there is no predominantly clear prior for how well CO_2 emissions growth should perform even with knowledge of its outperformance in addressing the equity premium puzzle in the U.S. market, we aggregate the data at the regional and global levels. Doing so comes with benefits and costs. First, analysis at regional and global levels gives us a macro-view of the ability of the CO_2 emissions measure to access consumption in the out-of-U.S. setting. Second, aggregation can alleviate the effect caused by trade and outsourcing in the recent period. Third, but very importantly, it offers some insights into the performance of CCAPM over a long and historical sample, which includes periods that the traditional expenditures-based consumption measures do not cover.

On the other hand, tests using world-level or regional-level data require a strong assumption about financial integration across financial markets that does not always hold in reality. In addition, the emissions-based measure is still prone to the impact of fuel efficiency changes and energy conservation concerns in the later periods. We estimate the Euler equation for Europe and the world separately using their CO_2 emissions growth and the market excess returns. Table 3, Panel A (Panel B), presents the estimates for Europe (the world) over three sample periods: the full sample, the pre-oil-crisis sample, and the post-oil-crisis. The CO_2 emissions growth measure delivers a reasonable estimate for the RRA coefficient in the pre-oil-crisis period and in the full sample period, both in Europe and globally. Specifically, the RRA estimated using CO_2 emissions growth in the European market is 6.23 over the pre-oil-crisis period and 9.67 over the full sample; the estimated RRA in the world market is 9.07 over the pre-oil-crisis period and 12.22 over the full sample. Similar to the finding using U.S. data, we find that the ability of CO_2 emissions growth to explain the European market risk premium and the world market risk premium weakens over time. This can be seen in Fig 3, where we plot the RRA estimated for the European market and the world market using a rolling window of 50 years starting from 1907: the estimated RRA coefficient clearly increases in the later part of the sample. Taking the post-oil-crisis sample as an example, the estimated RRA in the European and world markets is 24.40 and 48.22, respectively. That being said, CO_2 emissions growth still offers better or at least comparable performance relative to the expenditures-based measure. Over the same sample, the RRA required to match expenditures-based consumption growth to the market return excess return is double of that estimated using CO_2 emissions growth for Europe in terms of magnitude. However, the estimated RRA coefficient for the world is at a similar level (48.22 vs. 47.21).[5]

CO_2 emissions growth leads to sensible estimates for the model-implied risk-free rate in

[5]The standard error of the RRA coefficient estimated using CO_2 emissions growth in the post-oil-crisis is "blown up" and thus denoted as "-." This has to do with the choice of using the efficient variance-covariance matrix in the second stage of GMM, a choice that is intended to maximize the asymptotic information in the sample of the model. The downside of using the efficient matrix is that it may blow up standard errors rather than improve pricing errors as explained by Cochrane (1996).

the pre-oil-crisis period but mixed results in the post-oil-crisis period. In the pre-oil-crisis sample, the model-implied risk-free rate is at 5.18% in the European market and 7.31% in the world market. Over the full sample, the implied risk-free rate is at 5.14% in the world market, but it takes a negative value of -6.20% in the European market. The negative value in Europe is mainly driven by the post-oil-crisis observations: the implied risk-free rate is -28.28% over that period. The implied risk-free rate also takes a very high level of 57.66% in the world in the post-oil-crisis period. Nevertheless, using the same sample, we find that the implied risk-free rate using the expenditures-based consumption growth is at an enormous level: 109.82% for Europe and 227.07% for the world. Such unreasonable magnitudes of these estimates indicate a failure in fitting the expenditures-based consumption measure to the CCAPM framework to explain stock returns in Europe and the world. However, despite the mixed results in the post-oil-crisis period, the CO_2-emissions-based consumption measure still partially alleviates the joint equity risk premium and implied risk-free rate puzzle better than the traditional expenditures-based measure.

2.3 Other countries and regions

There is less analysis on testing the CCAPM in international stock markets relative to analysis conducted using U.S. data. This is largely because of the lack of data on both stock returns and consumption at the country level. Most of the analyses rely on the country-level stock indices data from the Morgan Stanley Capital International (MSCI), which starts in 1970 for developed countries and 1990 for most of the emerging countries. Consumption data mainly come from the International Financial Statistics (IFS) of the International Monetary Fund covering the period that goes back to at most 1960 for a small selection of countries. Even using the limited data available, the literature has documented some strong evidence of equity premium puzzles in international stock markets.[6] As a representative example, see

[6] This research includes Wheatley (1988), Braun et al. (1993), Chue (2002) and Sarkissian (2003), Darrat et al. (2011), and Li and Zhong (2005).

Campbell (2003), who finds that, using data from 1970 to 1999 for over eleven international markets, the required levels of risk aversion to justify the high equity market risk premia we observe in international stock markets are often with magnitudes of over a hundred and even over a thousand for some countries.

We test CO_2 emissions growth as a proxy for consumption risk under the CCAPM framework for a list of fifteen international markets outside of the United States. These countries include Australia, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Netherlands, Norway, South Africa, Spain, Sweden, Switzerland, and United Kingdom. The CO_2-emissions-based proxy benefits us by extending the coverage in both length and breadth compared with other consumption growth proxies. By matching the CO_2 emissions growth data with countries' equity market indices data from the Global Financial Database, we are able to estimate the RRA coefficient for these fifteen countries over samples that span on average over 100 years.

[Insert Table 4 Here]

Table 4 presents the estimated relative risk aversion coefficients and the implied risk-free rates for each of these fifteen countries estimated using countries' CO_2 emissions growth as proxies for their household consumption growth over their longest available sample, that is, the pre- and the post-post-oil-crisis subsamples. Over the full sample, the average relative risk aversion coefficient is about 6.58 across all countries, and almost all countries have an estimated RRA of below 10.[7] Similar findings are documented in the pre-oil-crisis sample, with an average estimated RRA coefficient of 6.55. Qualitatively speaking, the CO_2-emissions-based consumption measure yields better estimates in the pre-oil-crisis period: all countries have positive RRA estimates for 13 of 15 countries; the estimated RRAs in the pre-oil-crisis sample are lower than the ones estimated in the full sample. The post-oil-crisis

[7] The average is calculated over the absolute value of countries' estimated RRAs. Only three countries have negative estimated RRAs: Denmark, France, and Norway.

sample delivers larger RRAs compared to the earlier sample; the estimated RRAs vary from 2.86 in Switzerland to 75.73 in Australia. Most of the countries have an RRA between 10 and 20. Three countries have negative but small RRAs: they are Canada, Denmark, and Finland. These findings are in line with our earlier findings; that is, the CO_2-emissions-based measure performs better in the earlier sample using U.S. and regional data. In terms of the model-implied risk-free rate, while a number of countries have negative values, the magnitude of those who have positive implied risk-free rates is quite reasonable.

A couple of issues remain puzzling. First, a small number of countries (namely, Denmark, Finland, and France) have negative RRA estimates using the CO_2 emissions measure, and this occurs mainly in the pre-oil-crisis period. Second, the implied real risk-free rates are negative for several countries. This could be due to the quality of the CO_2 emissions data or stock market data for some of these countries or for other reasons. We do not have good answers for these puzzles for now, but we think these are valuable points that researchers could look at in future research to help us to better understand the importance of consumption risk in explaining asset returns across countries.[8]

3. Cross-sectional equity premium

In this section, we investigate whether the growth rate of CO_2 emissions can serve as a proxy for consumption risk in explaining the observed cross-sectional differences in stock returns. As described in Jagannathan and Wang (2007), the linearized version of the Euler equation

[8] One possible explanation that some estimation results for European region and countries are less intuitive, especially for the post oil crisis period, is that CO_2 emissions could also proxy for climate change risk, which has become a major concern for those countries over the past decades. Several recent studies focus on the relation between climate change risk and asset prices, including Litterman (2011), Giglio et al. (2015), Andersson et al. (2016), Bansal et al. (2016a), Bansal et al. (2016b), Karp and Rezai (2018), Daniel et al. (2019), Krueger et al. (2019) , and Hong et al. (2019).

(Equation 1) can be expressed as

$$E[R^e_{t+1}] \approx \gamma \beta R^f Cov(\frac{C_{t+1}}{C_t}, R^e_{t+1}). \tag{2}$$

Equation (2) implies that, under the standard assumptions of CCAPM, the cross-sectional variation in expected excess returns is determined by the correlation between assets' returns and the consumption risk measured by consumption growth. We perform Fama-MacBeth regressions using CO_2 emissions growth. Specifically, we first run time-series regressions for test assets' excess returns on CO_2 emissions growth to compute assets' corresponding consumption betas. We then estimate the price of consumption risk at each time t by performing a cross-sectional regression of assets' excess returns on the estimated beta loadings. The unconditional market price of consumption risk is computed as the time-series average of the estimated prices of risk. A constant term is included in both stages of regressions to ensure the first-stage β estimate is accurate and to allow for an evaluation of the pricing efficiency in the second stage. We are interested in two things: first, whether the consumption risk proxied using CO_2 emissions growth is priced in the stock market with a significant price of risk, and, second, whether it has good pricing power reflected in a small constant term in the second-stage regression and a small RMSE.

[Insert Table 5 Here]

Table 5 presents the results from the Fama-MacBeth two-step regressions using twenty-five U.S. portfolios sorted by size and book-to-market ratio as test assets. That the U.S. stock portfolio data are available from 1929 offers us a long time series of 86 years to conduct the test. We estimate factor risk premia for five different models: (1) a one-factor model with CO_2 emissions growth; (2) a one-factor model with the per capita nondurable goods and services expenditures growth; (3) a two-factor model with CO_2 emissions growth and expenditures growth; (4) a two-factor model with CO_2 emissions growth and the market factor; and (5) a two-factor model with expenditures growth and the market factor. For each model, we report the price of risk for each factor and its t-statistics computed based on Newey and West (1987) three-lagged standard errors. An average of the constant terms in the second-stage regression is also presented as a measure of pricing precision. In a one-factor model without controls, CO_2-emissions-based consumption growth yields a positive price of risk, which is statistically significant. This indicates that CO_2 emissions growth indeed captures consumption risk, which in turn explains the cross-sectional variation in excess returns of the Fama-French 25 portfolios formed using U.S. stocks. The constant term is small and statistically insignificant. Using the CO_2-emissions-based consumption growth measure, the average pricing error for the Fama-French 25 portfolios is 3.69% per year with a RMSE of 2.21% per year. The NIPA nondurable goods and services expenditures-based measure, on the other hand, has a weak pricing power, because its estimated price of risk is not statistically significant when used in a single-factor model alone or with controls. In addition, estimates for the constant term are statistically nonzero. Overall, the CO_2 emissions measure delivers the lowest pricing error and the smallest RMSE among all five linear models considered. The pricing power of this growth remains significant after controlling for the market risk factor or the expenditures-based consumption growth measure.

[Insert Table 6 Here]

We then assess whether CO_2 emissions growth has cross-sectional pricing power in the international markets. Because of the lack of and/or low-quality portfolio-/stock-level data for international markets in earlier periods, we implement the standard Fama-MacBeth procedure on the twenty-five global portfolios and twenty-five European portfolios from Kenneth French's data library with a sample period of 1991 to 2015. These portfolios are constructed by sorting individual stocks in that market by size and book-to-market ratio. Table 6 presents the second-stage price of risk for both CO_2 emissions growth and the expenditures-based consumption growth measures. We find that CO_2 emissions growth delivers a positive price of risk in pricing both the European portfolios and the world portfolios. This holds even if we control for the expenditures-based consumption growth and/or the market excess return. In contrast, the expenditures-based consumption growth measure can sometimes yield a negative price of risk when it is used as the single factor in explaining 25 twenty-five world portfolios or when it is used together with CO_2 emissions growth. In addition, tests using CO_2 emissions growth always yield higher adjusted R^2 than tests using expenditures-based consumption growth in an one factor setting and/or a two factors setting controlling for the market factor. However, the statistical significance of the price of risk on both CO_2 emissions growth and expenditures-based consumption growth are not significant in all cases. The weak pricing power does not come with too much of a surprise as tests are performed over a very short sample of 25 years of annual data due to its availability and, more importantly, as shown in earlier sections, CO_2 emissions growth performs less effectively in the recent period in terms of capturing the consumption risks in Europe and the world. Thus, we would expect the cross-sectional pricing power to improve in earlier sample and when longer data are available.

4. Conclusion

In this paper, we use CO_2 emissions as a proxy for households' consumption in testing the CCAPM with CRRA utility function for the United States and fifteen other international markets over their full history of available stock market data, that is, over 100 years. CO_2 emissions are closely related to households' consumption as a broad range of consumption involves emissions of CO_2, including forms of consumption that are difficult to capture by other alternative consumption measures like transportation and housing. Our measure also has favorable properties: it has a high correlation with stock market returns and is more volatile than the canonical expenditures-based consumption measure.

Our empirical results deliver a number of important findings. Using the annual growth rate of CO_2 emissions as a proxy for the consumption risk, our estimation achieves a very reasonable value for the relative risk aversion coefficient of around 6 and an implied real risk-free rate of 0.63% over the full sample of 1872–2015 in the United States under the CCAPM framework with CRRA utility. The CO_2-emissions-based measure also helps resolve the equity risk premium in international markets: it delivers an estimated RRA of 10 in Europe, 12 in the world, and 7 in fifteen other international markets. CO_2-emissions-based consumption growth also contributes to explaining the cross section of stock returns. Specifically, it explains returns of the U.S. stock portfolios with a positive and significant price of risk and the smallest pricing error and RMSE among all models considered, including ones controlling for the market factor and the expenditures-based consumption growth measure. Lastly, the benefit of our CO_2 emissions measure, in terms serving as a better measure of consumption under the CCAPM framework relative to the expenditures-based measure, is persistent over time, although we do observe a better performance in the pre-oil-crisis period relative to the post-oil-crisis period. This result supports Chen and Lu (2017) in terms of the elements of households' consumption that CO_2 emissions capture change over time: CO_2 emissions can be better exploited to capture important time-varying components of households' consumption and can be used in a more complex CCAPM framework in understanding its relation with asset prices.

References

Mats Andersson, Patrick Bolton, and Frédéric Samama. Hedging climate risk. *Financial Analysts Journal*, 72(3):13–32, 2016.

RJ Andres, DJ Fielding, G Marland, TA Boden, N Kumar, and AT Kearney. Carbon dioxide emissions from fossil-fuel use, 1751–1950. *Tellus B*, 51(4):759–765, 1999.

Ravi Bansal, Dana Kiku, and Marcelo Ochoa. Price of long-run temperature shifts in capital markets. *Working paper*, 2016.

Ravi Bansal, Marcelo Ochoa, and Dana Kiku. Climate change and growth risks. *Working paper*, 2016.

Ravi Bansal and Amir Yaron. Risks for the long run: A potential resolution of asset pricing puzzles. *The journal of Finance*, 59(4):1481–1509, 2004.

G. Marland Boden, T.A. and R. J. Andres. Estimates of global, regional, and national annual co2 emissions from fossil-fuel burning, hydraulic cement production, and gas flaring: 1950-1992. *Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.*, 1995.

Phillip A Braun, George M Constantinides, and Wayne E Ferson. Time nonseparability in aggregate consumption: International evidence. *European Economic Review*, 37(5):897–920, 1993.

Douglas T Breeden. An intertemporal asset pricing model with stochastic consumption and investment opportunities. *Journal of Financial Economics*, 7(3):265–296, 1979.

John Y Campbell. Asset prices, consumption, and the business cycle. *Handbook of Macroeconomics*, 1:1231–1303, 1999.

John Y Campbell. By force of habit: A consumption-based explanation of aggregate stock market. *The Journal of Political Economy*, 107(2):205–251, 1999.

John Y Campbell. Consumption-based asset pricing. *Handbook of the Economics of Finance*, 1:803–887, 2003.

Zhuo Chen and Andrea Lu. Seeing the unobservable from the invisible: The role of CO2 in measuring consumption risk. *Review of Finance*, 22(3):977–1009, 2017.

Timothy K Chue. Time-varying risk preferences and emerging market co-movements. *Journal of International Money and Finance*, 21(7):1053–1072, 2002.

John H Cochrane. A cross-sectional test of an investment-based asset pricing model. *Journal of Political Economy*, 104(3):572–621, 1996.

Zhi Da, Wei Yang, and Hayong Yun. Household production and asset prices. *Management Science*, 62(2):387–409, 2015.

Kent D Daniel, Robert B Litterman, and Gernot Wagner. Declining co2 price paths. *Proceedings of the National Academy of Sciences*, 116(42):20886–20891, 2019.

Ali F Darrat, Bin Li, and Jung Chul Park. Consumption-based capm models: International evidence. *Journal of Banking & Finance*, 35(8):2148–2157, 2011.

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

Stefano Giglio, Matteo Maggiori, Johannes Stroebel, and Andreas Weber. Climate change and long-run discount rates: Evidence from real estate. *Working paper*, 2015.

Lars Peter Hansen and Kenneth J Singleton. Stochastic consumption, risk aversion, and the temporal behavior of asset returns. *Journal of political economy*, 91(2):249–265, 1983.

Harrison Hong, Frank Weikai Li, and Jiangmin Xu. Climate risks and market efficiency.

Journal of Econometrics, 208(1):265–281, 2019.

Larry Karp and Armon Rezai. Asset prices and climate policy. *Working paper*.

Philipp Krueger, Zacharias Sautner, and Laura T Starks. The importance of climate risks for institutional investors. *Swiss Finance Institute Research Paper*, (18-58), 2019.

Yuming Li and Maosen Zhong. Consumption habit and international stock returns. *Journal of Banking & Finance*, 29(3):579–601, 2005.

Robert Litterman. Pricing climate change risk appropriately. *Financial Analysts Journal*, 67(5):4–10, 2011.

Robert E Lucas Jr. Asset prices in an exchange economy. *Econometrica*, 46(6):1429–1445, 1978.

Christopher J Malloy, Tobias J Moskowitz, and Annette Vissing-Jørgensen. Long-run stockholder consumption risk and asset returns. *The Journal of Finance*, 64(6):2427–2479, 2009.

Gregg Marland and Ralph M Rotty. Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950-1982. *Tellus B: Chemical and Physical Meteorology*, 36(4):232–261, 1984.

Rajnish Mehra and Edward C Prescott. The equity premium: A puzzle. *Journal of monetary Economics*, 15(2):145–161, 1985.

Jesper Munksgaard, Klaus Alsted Pedersen, and Mette Wien. Impact of household consumption on CO2 emissions. *Energy economics*, 22(4):423–440, 2000.

Whitney K Newey, Kenneth D West, et al. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica*, 55(3):703–708, 1987.

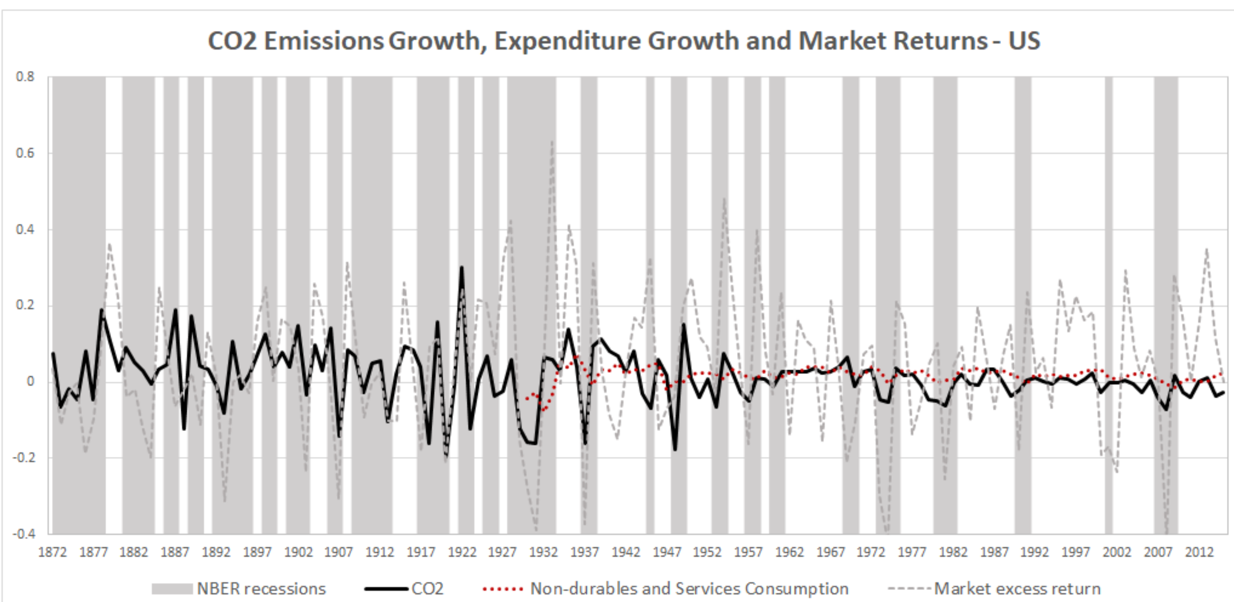
Alexi Savov. Asset pricing with garbage. *The Journal of Finance*, 66(1):177–201, 2011.

Philippe Weil. The equity premium puzzle and the risk-free rate puzzle. *Journal of Monetary Economics*, 24(3):401–421, 1989.

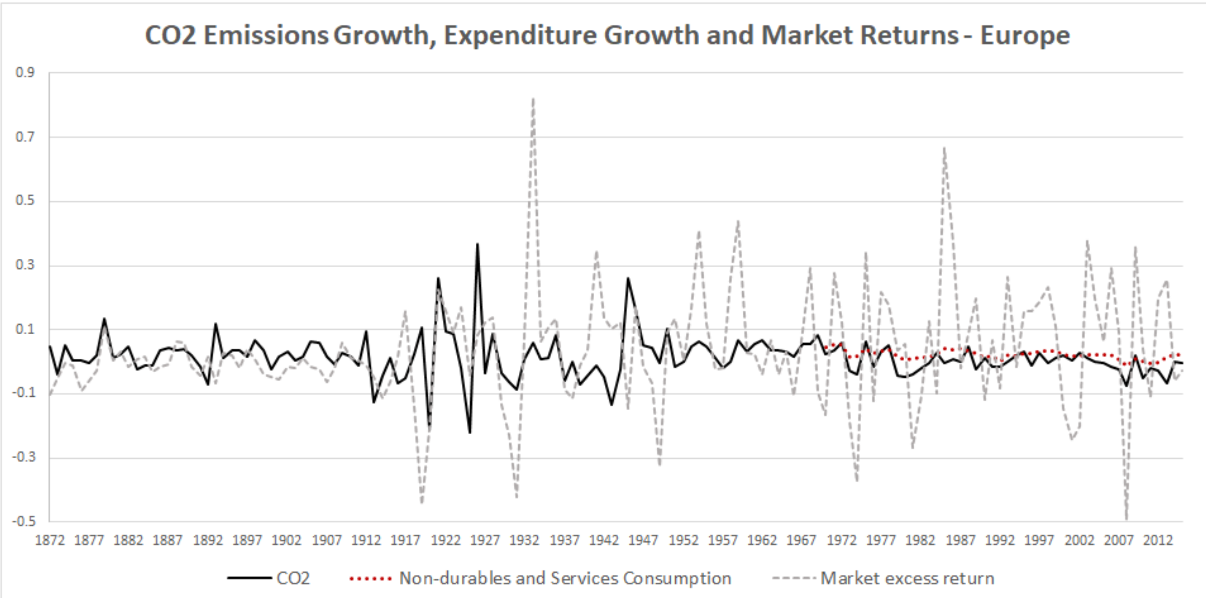
Figure 1: CO_2 emissions growth and expenditures growth

Figure 1 compares the time series of the annual CO_2 emissions growth to the consumption expenditures growth. Panel A presents the U.S. time series: the solid line represents the annual growth rate of the per capita CO_2 emissions; the red dotted line represents the annual per capita growth of nondurables goods and services expenditures from NIPA; the gray dashed line represents the annual real excess returns of the U.S. stock market; and the shaded bands indicate National Bureau of Economic Research (NBER) recessions. Panels B and C present the time series for Europe and the world. Within each figure, the solid line, the dotted line, and the dashed line represent CO_2 emissions growth, the households and NPISHs Final consumption expenditures growth, and the excess returns of the corresponding region. Growth rates and returns are demeaned and expressed as percentages. The sample period for CO_2 emissions growth and stock returns are 1872–2015 for the United States and Europe and 1907–2015 for the world. The sample period for consumption growth is 1929–2015 for the United States and 1970–2015 for Europe and the world.

(a) U.S. time series



(b) Europe time series



(c) World time series

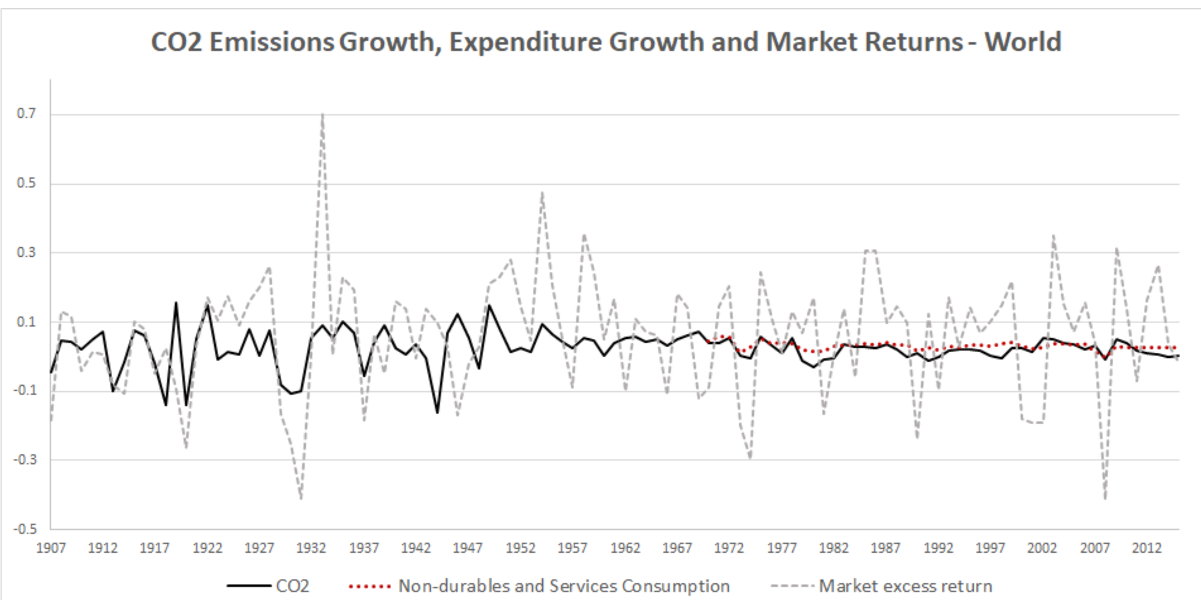


Figure 2: Time-varying RRA estimated using CO_2 emissions growth: The United States

Figure 2 plots the time series of the relative risk aversion (RRA) coefficients estimated for the United States using the growth rate of CO_2 emissions as a proxy of consumption growth over a rolling window of 50 years. Specifically, the RRA in year t is estimated using data from year t-49 to t. The estimated RRAs are represented by the solid line. We also plot the RRAs estimated using nondurable goods and services expenditures growth on the dotted line for comparison purposes. The estimates start in 1921 with an estimation window of 1872–1921 using the CO_2 emissions measure, and they start in 1978 for the expenditures-based measure. All estimates end in 2015.

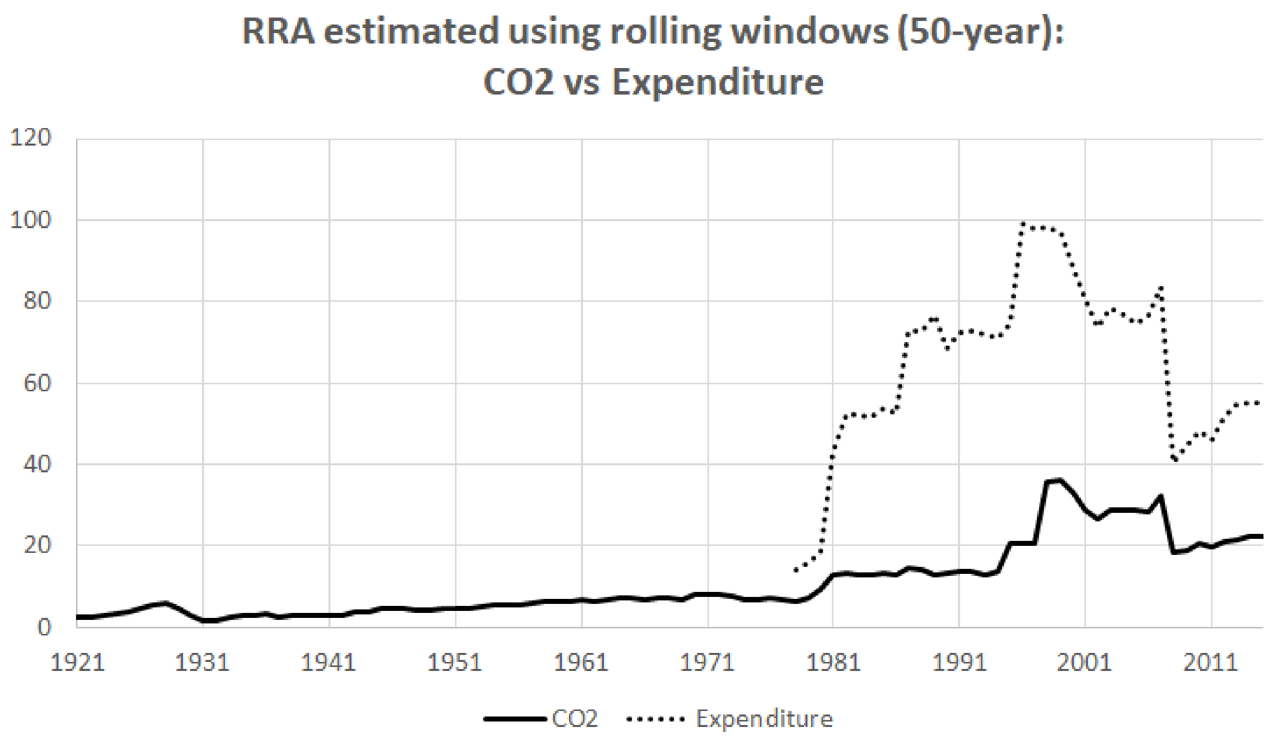


Figure 3: Time-varying RRA estimated using CO_2 emissions growth: Europe and the world

Figure 3 plots the time series of the relative risk aversion (RRA) coefficients estimated in Europe and the world using the growth rate of CO_2 emissions as a proxy of consumption growth over a rolling window of 50 years. Specifically, the RRA in year t is estimated using data from year t-49 to t. RRAs estimated in Europe and the world are represented by the dashed and dotted lines, respectively. The estimates start in 1956 with an estimation window of 1907–1956 and end in 2015.

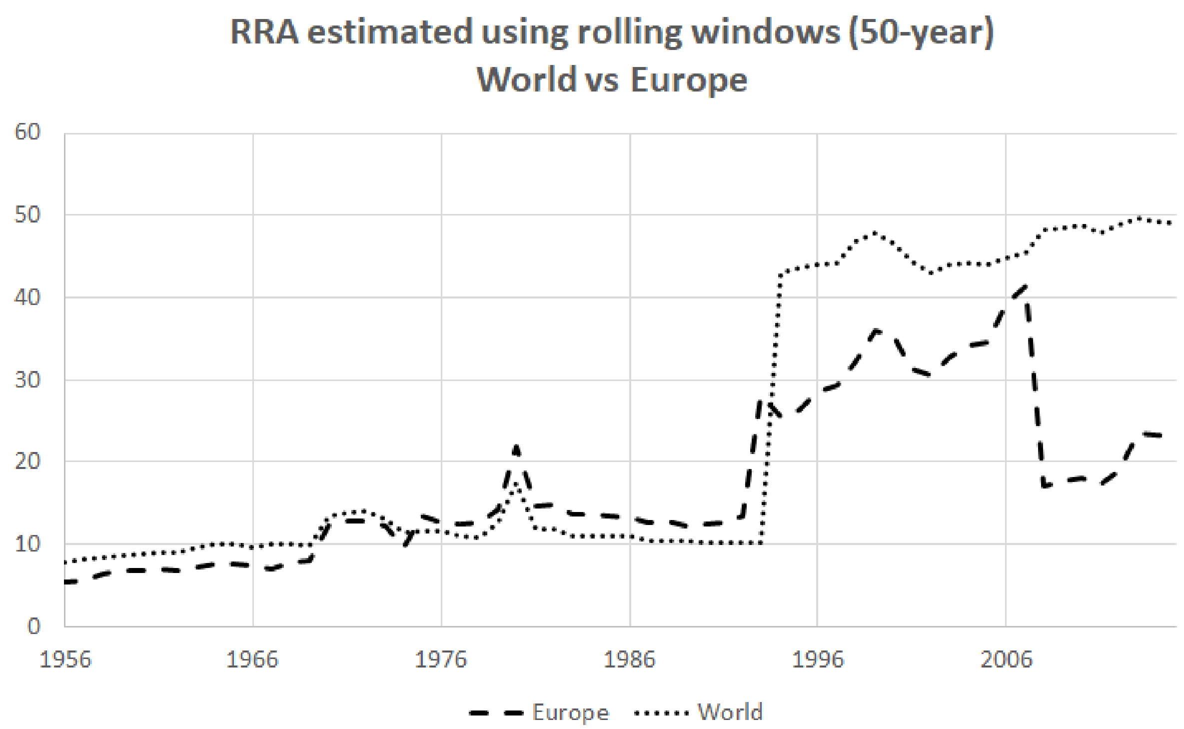


Table 1: Summary statistics for the CO_2 emissions growth measure

Table 1 presents summary statistics for CO_2 emissions growth. Statistics include the mean, standard deviation, and AR(1) autocorrelation coefficient of CO_2 emissions growth for the United States, Europe, and the world and their correlations with the corresponding stock market returns R^M. We present the summary statistics for three sample periods: the full sample of 1872–2015, the pre-oil-crisis sample of 1872–1973, and the post-oil-crisis period of 1974–2015, with the exception for the world, where its first observation starts in 1907. All statistics are expressed as percentages.

	Full sample			Pre-oil-crisis			Post-oil-crisis		
	U.S.	Europe	World	U.S.	Europe	World	U.S.	Europe	World
Mean	1.40	1.42	2.49	2.29	2.15	2.90	-0.76	-0.35	1.85
SD	7.48	6.80	5.29	8.58	7.73	6.53	2.65	3.05	2.09
AR(1) coeff.	-14.52	-10.68	8.94	-20.52	-15.26	-3.45	22.71	3.55	27.81
Corr. with R^M	42.05	18.44	39.73	44.66	17.91	45.24	49.44	28.75	34.89

Table 2: Relative risk aversion estimation: Evidence from the United States

Table 2 presents the CCAPM parameters estimated using CO_2 emissions growth and market real excess returns in the United States. CO_2 emissions growth acts as a proxy for consumption risk in the CCAPM. Estimates are obtained by estimating the following Euler equation using the GMM:

$$E[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}R^e_{t+1}] = 0.$$

The subject discount factor, β, is set to be 0.95. The relative risk aversion (RRA) coefficient, γ, is presented with Newey-West three-lagged adjusted GMM standard errors displayed in parentheses. The model-implied risk-free rates (R^f) are computed based on the estimated RRA and expressed as percentages. Pricing errors are defined as $\sqrt{g_T' g_T / N}$, where N is the number of test assets. Panel A presents the estimates using CO_2 emissions growth. Panel B compares the estimates obtained using CO_2 emissions growth and ones obtained using nondurable goods and services (ND&S) expenditures growth. Estimates are presented for three sample periods: the full sample (1872–2015), the pre-oil-crisis period (1872–1973), and the post-oil-crisis period (1974–2015).

A. Estimates using the CO_2 emissions growth

	Full sample 1872–2015	Pre-oil-crisis 1872–1973	Post-oil-crisis 1974–2015
RRA(γ)	6.24	5.27	14.39
(SE)	(2.22)	(2.12)	(9.74)
Implied R^f (%)	0.63	4.32	-13.14
Pricing error	0.0000	0.0000	0.0000

B: Comparison between estimates using different consumption growth proxies

	Full sample 1872–2015		Pre-oil-crisis 1872–1973		Post-oil-crisis 1974–2015	
	Expenditures	CO_2	Expenditures	CO_2	Expenditures	CO_2
RRA(γ)	16.24	6.75	11.99	5.91	43.62	14.39
(SE)	(8.13)	(3.30)	(7.76)	(3.30)	(27.47)	(9.74)
Implied R^f (%)	31.72	-4.18	24.77	-0.61	92.36	-13.61
Pricing error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 3: Relative risk aversion estimation: Evidence from Europe and the world

Table 3 presents the CCAPM parameters estimated using CO_2 emissions growth and market real excess returns in Europe and the world. CO_2 emissions growth acts as a proxy for consumption risk in the CCAPM. Estimates are obtained by estimating the following Euler equation using the GMM:

$$E[\beta(\frac{C_{t+1}}{C_t})^{-\gamma}R^e_{t+1}] = 0.$$

The subject discount factor, β, is set to 0.95. The relative risk aversion (RRA) coefficient, γ, is presented with Newey-West three-lagged adjusted GMM standard errors displayed in parentheses. The model-implied risk-free rates (R^f) are computed based on the estimated RRA and expressed as percentages. Pricing errors are defined as $\sqrt{g_T' g_T/N}$, where N is the number of test assets. Panel A presents results for Europe, and Panel B presents results for the world. The test asset for these two markets is the real market excess returns, obtained from Thomson Reuters Credit Suisse Yearbook and the Global Financial Database. We present estimates for three sample periods: the full sample (1907–2015), the pre-oil-crisis period (1907–1973) and the post-oil-crisis period (1974–2015). For comparison purposes, we also present the estimates obtained using households' final consumption expenditures growth as a proxy for consumption growth for the post-oil-crisis period.

A. The European market

	Full sample	Pre-oil-crisis	Post-oil-crisis	
	1907–2015	1907–1973	1974–2015	
	CO_2	CO_2	CO_2	Expenditures
RRA(γ)	9.67	6.23	24.40	42.87
(SE)	(3.83)	(4.27)	(17.44)	(21.77)
Implied R^f (%)	-6.20	5.18	-28.28	109.82
Pricing error	0.0000	0.0000	0.0000	0.0000

B. The World market

	Full sample	Pre-oil-crisis	Post-oil-crisis	
	1907–2015	1907–1973	1974–2015	
	CO_2	CO_2	CO_2	Expenditures
RRA(γ)	12.22	9.07	48.22	47.21
(SE)	(5.28)	(4.68)	-	(22.63)
Implied R^f (%)	5.14	7.31	57.66	277.07
Pricing error	0.0000	0.0000	0.0000	0.0000

Table 4: Relative risk aversion estimation: International markets

Table 4 reports the estimated relative risk aversion (RRA) coefficient, γ, and implied risk-free rate, R^f, for sixteen international markets using GMM estimation. The moment condition for each country is

$$E[\beta(\frac{C^i_{t+1}}{C^i_t})^{-\gamma} R^{e,i}_{t+1}] = 0,$$

where $\frac{C^i_{t+1}}{C^i_t}$ is the growth rate consumption in country i, proxied by country i's CO_2 emissions growth, and $R^{e,i}_{t+1}$ is the excess return of country i's stock market excess return. The subject discount factor, β, is set to 0.95. The relative risk aversion (RRA) coefficient, γ, is presented with Newey-West three-lagged adjusted GMM standard errors displayed in parentheses. The model-implied risk-free rates (R^f) are computed based on the estimated RRA and expressed as percentages. The parameters for each country are estimated using each country's longest available sample, the pre-oil-crisis sample (before 1974), and the post-oil-crisis sample (1974–2015).

Country	Available sample	Full sample RRA	Full sample Implied R^f	Pre-oil-crisis RRA	Pre-oil-crisis Implied R^f	Post-oil-crisis RRA	Post-oil-crisis Implied R^f
Australia	1871–2015	10.04	13.90	8.91	15.49	75.73	<0
		(-)		(-)		(136.81)	
Belgium	1897–2015	5.86	<0	4.12	<0	16.12	<0
		(1.9)		(2.41)		(8.98)	
Canada	1871–2015	10.70	0.10	8.92	6.80	48.00	<0
		(4.26)		(4.2)		(-)	
Denmark	1874–2015	-0.83	2.79	2.77	11.17	-8.11	<0
		(-)		(-)		(-)	
Finland	1913–2015	2.24	<0	1.84	<0	-0.59	5.19
		(0.48)		(0.46)		(-)	
France	1871–2015	9.61	3.60	8.65	1.85	-0.34	5.48
		(3.12)		(3.87)		(-)	
Germany	1871–2015	3.48	<0	3.46	<0	31.83	<0
		(-)		(-)		(17.2)	
Ireland	1935–2015	8.01	<0	1.70	7.39	19.89	<0
		(-)		(-)		(10.4)	
Italy	1925–2015	0.87	3.79	0.82	3.23	16.21	<0
		(-)		(-)		(12.94)	
Japan	1886–2015	5.86	<0	5.09	1.81	15.42	0.27
		(2.79)		(2.67)		(12.19)	
Netherlands	1951–2015	14.10	<0	44.64	13.31	12.89	<0
		(4.81)		(23.75)		(5.12)	
Sweden	1871–2015	0.97	7.37	0.63	7.34	21.69	<0
		(-)		(-)		(11.45)	
Spain	1941–2015	0.17	5.45	0.06	5.59	15.68	<0
		(-)		(-)		(11.76)	
Switzerland	1914–2015	3.01	<0	3.01	<0	2.86	3.10
		(-)		(-)		(-)	
United Kingdom	1871–2015	4.20	<0	4.12	<0	37.88	<0
		(-)		(-)		(45.12)	

Table 5: Cross-sectional pricing of U.S. stock portfolios

Table 5 reports results from the Fama-MacBeth two-pass regressions of the linear factor models with twenty-five U.S. portfolios sorted by size and book-to-market ratio as test assets. A cross-sectional constant is included in the estimation. CO_2 is annual CO_2 emissions per capita growth. Expenditures are the annual growth of seasonally adjusted per capita expenditures on nondurable goods and services (ND&S) from NIPA. Market is the market excess return. We estimate factor risk premia for five different models: (1) a one-factor model with CO_2 emissions growth; (2) a one-factor model with ND&S growth; (3) a two-factor model with CO_2 emissions growth and ND&S growth; (4) a two-factor model with CO_2 emissions growth and the market factor; and (5) a two-factor model with ND&S growth and the market factor. A constant is included in the second-stage regression. Regression coefficients (factor risk premia) are reported, with t-statistics adjusted using Newey–West (1987) three-lagged corrections in parentheses. Root-mean-square errors (RMSEs) and adjusted R^2 are measured as percentages. The sample period is 1929–2015.

	CO_2	Expenditures	Market	Constant	RMSE	Adj. R^2
(1)	5.02			3.69	2.21	19.90
	(2.21)			(1.05)		
(2)		0.94		7.04	2.52	22.73
		(1.65)		(2.24)		
(3)	5.90	1.04		3.72	2.18	25.49
	(3.35)	(1.80)		(1.05)		
(4)	6.79		6.26	6.12	2.09	27.93
	(3.66)		(1.27)	(1.40)		
(5)		1.55	0.56	11.85	2.40	29.02
		(2.68)	(0.12)	(2.95)		

Table 6: Cross-sectional pricing of European and world stock portfolios

Table 6 reports results from the Fama-MacBeth two-pass regressions of the linear factor models with twenty-five size and book-to-market portfolios constructed using European stocks and stocks from developed markets as test assets. CO_2 is the annual CO_2 emissions growth. Expenditures are the annual growth of households and NPISHs final consumption expenditures from the World Bank. Market is the market excess return. We estimate factor risk premia for five different models: (1) a one-factor model with CO_2 emissions growth; (2) a one-factor model with ND&S growth; (3) a two-factor model with CO_2 emissions growth and ND&S growth; (4) a two-factor model with CO_2 emissions growth and the market factor; and (5) a two-factor model with ND&S growth and the market factor. A constant is included in the second-stage regression. Regression coefficients (factor risk premia) are reported, with t-statistics adjusted using Newey–West (1987) three-lagged corrections in parentheses. Root-mean-square errors (RMSEs) and adjusted R^2 are expressed as percentages. We present results for European stock portfolios in Panel A and results for world portfolios in Panel B. The sample period is 1991–2015.

A. Twenty-five European portfolios sorted by size and book-to-market ratio

	CO_2	Expenditures	Market	Constant	RMSE	Adj. R^2
(1)	2.43			4.18	1.97	19.48
	(1.62)			(0.77)		
(2)		0.82		2.88	2.37	13.26
		(1.35)		(0.47)		
(3)	2.64	0.30		7.85	1.86	22.83
	(1.68)	(0.65)		(1.56)		
(4)	2.36		-0.51	8.89	1.91	30.80
	(1.62)		(-0.10	(2.88)		
(5)		0.80	0.19	9.85	2.24	25.37
		(1.35)	(0.04	(3.02)		

B. Twenty-five world portfolios sorted by size and book-to-market ratio

	CO_2	Expenditures	Market	Constant	RMSE	Adj. R^2
(1)	0.64			4.40	1.93	20.21
	(0.94)			(1.18)		
(2)		-0.06		8.38	2.10	19.90
		(-0.16)		(1.95)		
(3)	0.66	-0.15		8.04	1.80	41.15
	(0.95)	(-0.39)		(1.89)		
(4)	0.76		-3.07	9.23	1.58	50.10
	(1.07)		(-0.60	(2.22)		
(5)		0.74	0.68	6.51	1.50	40.55
		(1.64)	(0.14)	(1.68)		

fbe.unimelb.edu.au/finance