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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

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Abstract

We study climate risk premiums in euro area corporate bond markets. As gauges of climate risk, we distinguish between physical and transition risks using textual analysis. Our findings show that, since the Paris agreement, physical risk is significantly priced in corporate bonds with longer-term maturities. Physical risk is also priced in bonds with shorter-term maturities, but the premium is smaller and less significant. The estimated physical risk premium reflects investors demanding higher future returns on bonds that underperform during adverse physical risk shocks. Our findings also point to a sizable transition risk premium, although the transition risk estimates are insignificant.

JEL codes: G12, Q51, Q54

Key Words: Climate risk, physical risk, transition risk, corporate bonds

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1 Introduction

Investors are wary of climate change. This is because climate change is a source of financial risk that affects asset prices through changes in physical or transition risk. Physical risk reflects the impact of chronic and acute physical events, whereas transition risk arises from the costly adjustment towards a low-carbon economy, typically prompted by changes in climate and environmental policies, technological advances, and/or shifts in public preferences.[1]

The materialisation of these climate risks has implications for asset pricing. In assets markets, investors have incentives to hedge against the risk of climate change by holding assets today that deliver higher returns during events of adverse climate shocks in the future (theory on the intertemporal hedging hypothesis is provided by Merton (1973); Campbell (1990)). By implication, investors may be willing to accept lower future returns on assets that are good hedges against climate change, thereby reducing the cost of capital for issuers.

There is a vast literature that supports the existence of transition risk premiums (e.g. Alessi et al. (2019); Bolton and Kacperczyk (2021); Ardia et al. (2020); Bua et al. (2021); Faccini et al. (2021); Görgen et al. (2020)) and physical risk premiums (e.g. Addoum et al. (2019); Hong et al. (2019); Kruttli et al. (2021)) in stock markets, especially after the Paris agreement. By contrast, the literature on climate risk pricing in corporate bond markets is scarce. To our knowledge, Huynh and Xia (2021) is the only study to investigate climate risk premiums in US corporate bond markets. Using the text-based index developed by Engle et al. (2020) as an indicator of climate risk, they conclude that investors in US corporate bond markets accept lower future returns on bonds that are good hedges against climate risk.

Yet, no study has so far focused on euro area corporate bond markets. Mapping the pricing effects of climate risk in corporate bond markets is especially relevant for the euro area because, relative to GDP, market-based debt finance plays a more prominent role in the euro area than in the US.[2]. While corporate debt has increased as a financing source on both sides of the Atlantic since the Global Financial Crisis (Berg et al. (2021)), the increase in the relative share of bond financing is particularly pronounced in the euro area (e.g. Cappiello et al. (2021); Darmouni and Papoutsi (2022)). In addition, climate risk premiums are likely to look different in Europe compared to the rest of the world, as the European Union plays a prominent role in climate regulations initiatives and is committed to becoming the first net-zero emissions continent.

In this paper, we fill the gap and estimate climate risk premiums in corporate bond markets for the euro area. Building on the findings by Huynh and Xia (2021), we contribute to the literature in three ways. First, by using the two novel text-based climate risk indicators developed by Bua

[1] Examples of chronic physical events are gradual shifts in wind and precipitation in the shorter-term, or sea levels, desertification and ocean temperatures in the longer-term, while examples of acute physical events are floods, droughts and wildfires.

[2] See for example the BIS debt securities statistics

et al. (2021) using scientific texts and news on climate change, we assess whether climate risk premiums in euro area corporate bond markets stem mostly from physical or transition risks. Different from previous studies that have used textual analysis to identify climate risk (Engle et al. (2020)), and with the corporate bond literature thus far focusing on climate change only as a single risk factor, our indices exploit news content to identify physical and transition risk shocks separately. Studying the individual effects of physical and transition risks is important, as these risks affect companies through different channels.[3] Second, different from the literature on corporate bonds, our analysis uses daily instead of monthly data on climate risk shocks and corporate bond prices. Daily data improve the identification of climate risk shocks using textual analysis, since the news coverage of climate change fluctuates rapidly. Moreover, daily data also provide for a more accurate quantification of climate risk premiums, because monthly data lack power to identify abnormal returns (see also Bessembinder et al. (2009)). Third, we investigate climate risk pricing in corporate bond markets using portfolio analysis and Fama-Macbeth cross-sectional regressions Fama and MacBeth (1973). In contrast to the fixed effects panel estimation approach by Huynh and Xia (2021), our empirical asset pricing strategy aligns our work with the corporate bond market literature, which relies on a combination of bond and stock market factors for the estimation of abnormal returns (e.g. Lin et al. (2011); Bali et al. (2017); Bai et al. (2019); Bali et al. (2021)).

Using data from January 2005 until September 2021, we follow three steps to estimate physical and transition risk premiums in euro area corporate bond markets. First, we capture climate risk 'betas' by estimating the sensitivities of bonds' excess returns to physical and transition risk shocks using daily data on corporate bond prices. Accordingly, bonds with negative physical and transition risk betas are those that provide bad hedges against physical and transition risks. Second, using monthly data, we sort corporate bonds into (quintile) portfolios by the climate risk betas so as to measure the cross-sectional relationship between climate risk and the future excess returns of bonds at the portfolio-level. For each portfolio, we also estimate measures of the risk-adjusted returns of portfolios using bond and stock market factors. Third, we examine the intertemporal relationship between the climate risk betas and future monthly bond returns using Fama-Macbeth cross-sectional regressions. Using these regressions, we additionally check for the persistence of the climate risk premiums by focusing on out-of-sample cumulative returns several months ahead. In line with the literature, we study the periods before and after the year of the Paris agreement separately.

Our findings show that, since the year of the Paris agreement, physical risk is significantly priced in euro area corporate bonds with relatively longer maturities, while the physical risk premium of bonds with shorter maturities is smaller and less significant. Accounting for bond characteristics,

[3] Companies exposed to physical risk can be affected through damaged assets and disruption of business operations. Depending on how fast and orderly the decarbonisation process occurs, companies exposed to transition risk may be affected by large swings in asset prices and stranded assets.

the physical risk premium for long-term bonds is negative and estimated to be 15 basis points 1-month ahead and 34 basis points 2- to 6-months ahead. The negative physical risk premium reflects investors demanding higher future returns on bonds that are bad hedges against physical risk, because bonds with negative physical risk betas especially underperform. Similar to the findings in the stock market literature, corporate bonds did not contain significant physical risk premiums before 2015, indicating that investors' incentives to hedge against physical risk intensified after the Paris agreement. By contrast, while the transition risk premium is also found to be negative, the estimations are mostly insignificant. Together, these findings identify a new risk factor for predicting the cross-sectional variation in future bond returns.

The rest of this paper is organised as follows. Section 2 describes the data. Section 3 discusses the results. Section 4 concludes.

2 Data

2.1 Corporate bond data

The analysis includes daily ISIN-level data on investment grade (IG) and high yield (HY) bonds issued in the euro area by non-financial and financial corporates. The sample starts in January 2005 and ends in September 2021. We combine data on individual bond price returns with information on bond characteristics that are commonly used in the literature, including remaining maturity, rating, outstanding amount (log) and illiquidity (indicated by bid-ask spreads). The bond- and firm-level data are taken from Bloomberg, while European market-level data are taken from iBoxx and the Kenneth French's data library. All bonds are traded in euros.

The selection of bonds is based on the ICE Bank of America (BofA) Global Corporate and High Yield indices (i.e. G0BC and HW00). Corporate bonds are qualified for the BofA indices when they have (1) a rating (provided by S&P, Fitch and Moody's), (2) more than 1 year to maturity, (3) at least 18 months to maturity at issuance, and (4) a fixed coupon schedule. Different from the literature focusing on the US, which generally uses the Financial Industry Regulatory Authority's Trade Reporting and Compliance Engine (TRACE) enhanced database, we do not include information on corporate bond transactions due to data constraints. While investigating the cross-section of corporate bond returns using transaction data is preferable, the BofA indices are used actively in derivative trading, which provides a strong incentive for accurate price data. We exclude matrix prices from the sample, as these are considered less reliable than dealer quotes.[4]

Following Bao et al. (2011), bonds are dropped when they are traded relatively little so as to facilitate the reliable estimation of a bond's exposure to climate risk. The trading activity of a

[4] In the final sample, excluding matrix-priced bonds, which are bonds that have no market price and are priced using the quoted prices of similar bonds, eliminates the observations of 2 bonds only.

bond is gauged from the availability of Bloomberg data on a bond's daily bid/ask spreads, since data on bid/ask spreads can only be available when the bond has been traded that day. More specifically, a bond is dropped when data on the daily bid/ask spreads is missing for more than 25 percent of the bond's life span. In line with Bali et al. (2021) and others, the sample is further restricted by excluding bonds that (i) are issued by non-publicly listed firms, (ii) are convertible, backed by mortgages or other assets, or linked to equity, (iii) are structured notes, (iv) have once traded below €5, and (v) price a floating coupon rate. Similar to Huynh and Xia (2021), bonds with a rating lower than B- are also excluded from the main regression analysis, since junk bonds generally are less liquid, which can lead to pricing errors (see for example Gebhardt et al. (2005) and Lin et al. (2011)).

In line with the literature, the corporate bond price returns are calculated as:

$$r_{i,t} = \frac{(P_{i,t} + AI_{i,t}) + C_{i,t} - (P_{i,t-1} + AI_{i,t-1})}{(P_{i,t-1} + AI_{i,t-1})} \tag{1}$$

where $P_{i,t}$ is the bond price, $AI_{i,t,}$ represents accrued interest, $C_{i,t}$ indicates the coupon payment, if any in the respective time period, and the subscripts i and t denote the bond and time period. Subsequently, to determine the excess price returns of corporate bonds, we subtract the 1-month OIS rate (based on €STR) - an indicator of the risk-free rate - from the individual corporate bond returns.[5]

2.2 Climate change shocks

To determine the corporate bond pricing effects of climate change, we update the daily text-based indicators of transition and physical climate risk shocks by Bua et al. (2021). The text-based indices exploit news content to identify physical and transition risk shocks. Investors use news as a source of information to update beliefs on climate change risks, with the assumption that news coverage on climate change intensifies amid rising climate risks. Different from previous studies that have identified climate change as a single risk factors (e.g. Engle et al. (2020)), these indices have the advantage of distinguishing between physical and transition risks, allowing the assessment of the different effects of physical and transition risk shocks on financial markets.

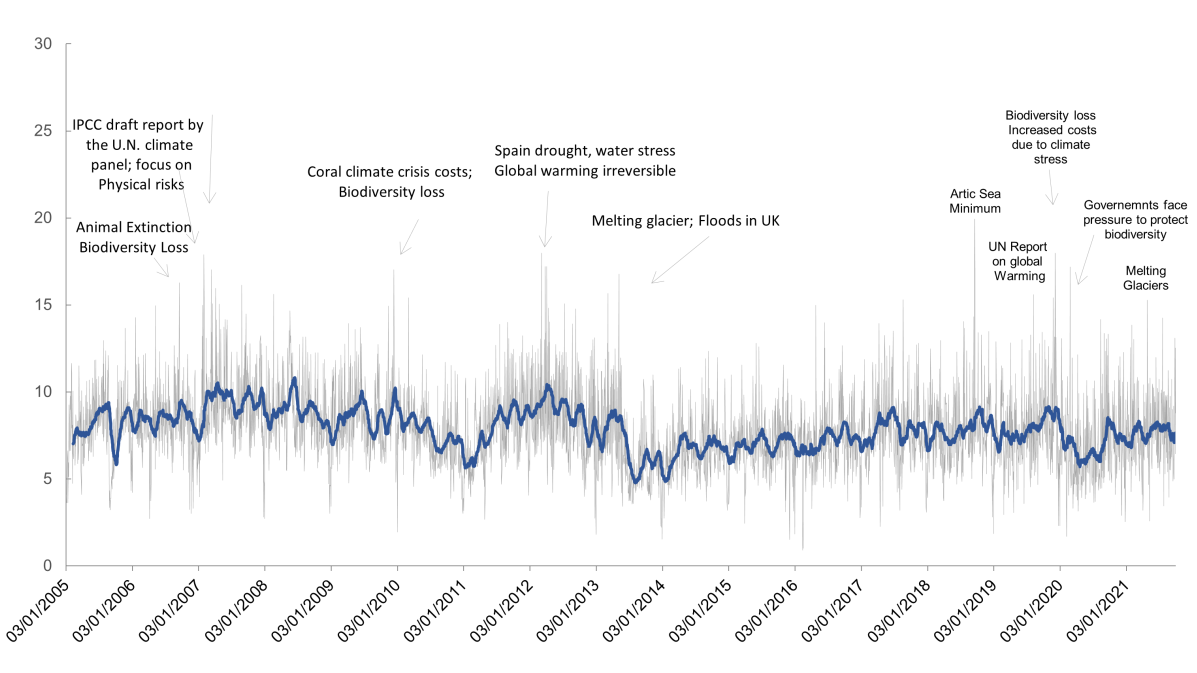
The textual identification of the climate risk shocks can be summarized in four main steps.[6] First, scientific and authoritative text documents on climate change topics are aggregated into physical and transition risk vocabularies. Similarly, an analogous list of term frequency scores is documented for daily aggregations of real-time Reuters news, referred to as daily Reuters news documents. Second, term frequency – inverse document frequency *(tf-idf)* scores are constructed for both the vocabularies and Reuters news documents, which indicate the extent to which a

[5]Data on the 1-month OIS rates start in August 2005. For the months before that, we use short-term German bond yields as an indicator of the risk-free rate.

[6]For a detailed description of the indices please refer to Bua et al. (2021).

term is frequent in a specific document, while infrequent in other documents (see also Gentzkow et al. (2019)). Third, physical and transition risk concern series are then constructed using *cosine similiarity* between the *tf-idf* scores of the vocabularies and Reuters news documents.[7] The concern indices roughly represent the portion of daily news corpus dedicated to either the topic of physical risk or transition risk.[8] Fourth, following the literature (e.g. Engle et al. (2020), we estimate physical and transition risk shocks as the residuals from autoregressive regressions of order 1 (i.e. an AR(1) process).

Figure 1: Physical risk concern



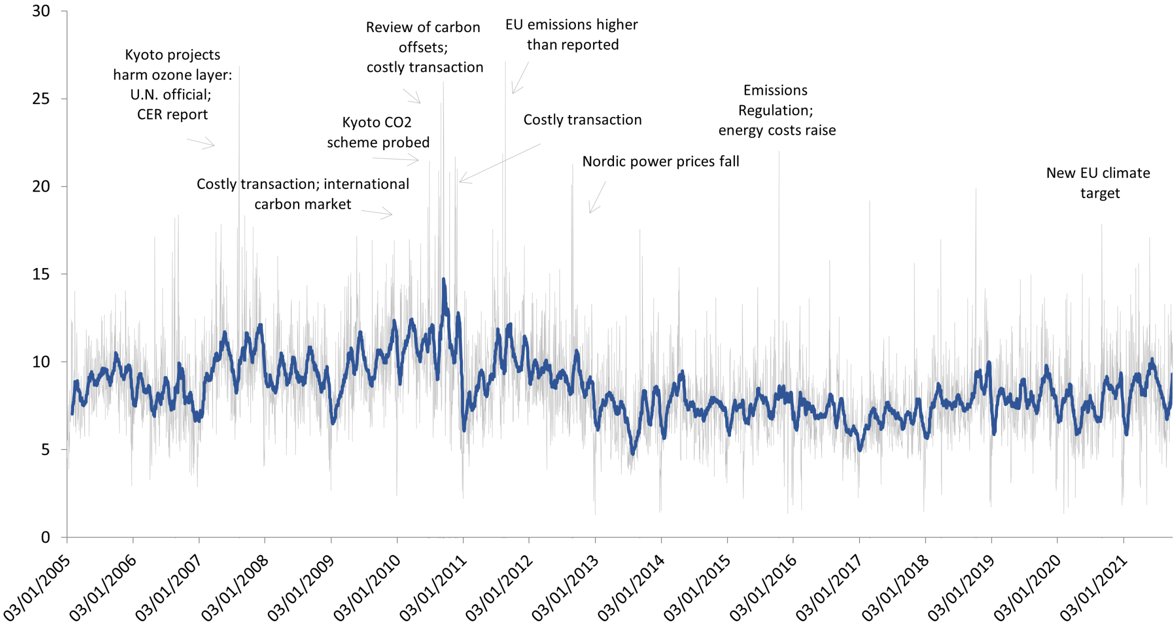
Notes: Daily physical risk concern with the major risk shock topics (vertical bars) for the period Jan 2005-Sep2021.

Figure 1 and Figure 2 show the daily physical and transition media concerns (i.e. not the estimated shocks) with the major risk shock topics (vertical bars) from January 2005 to September 2021. The physical risk concern index peaked on 19 September 2018, amid large discussions revolving the loss of arctic sea. Other spikes in physical risk concerns generally related to the loss of biodiversity, becoming more concentrated toward the end of the sample. The transition risk index peaked on 24 August 2011, with news on high levels of EU GHG emissions. The transition risk index furthermore peaked following news concerning climate regulation and measures to

[7]Cosine-similarity is a technique used in textual analysis to evaluate the similarity between pairs of texts. It expresses the angular distance between two pairs of text, where, the smaller the angular distance, the higher the cosine, and the higher the similarity. Put differently, we consider our physical and transition risk dictionaries as vectors, the direction of which depends on the intensity of each element, given by the *tf-idf* of vocabulary terms. This means that daily news which point in the same direction as the physical and transition risk vectors are assessed to discuss the physical and transition risk topics, respectively.

[8]'Daily news' is broadly defined such that, in addition to actual climate-related events, the concern indices can for instance also reflect speculation by the public, which is expected to drive asset prices.

Figure 2: Transition risk concern



Notes: Daily transition risk concern with the major risk shock topics (vertical bars) for the period Jan 2005-Sep2021.

curb GHG emissions (e.g. news regarding the EU carbon reform deal or the Kyoto Protocol, as well as news concerning the costs associated to the transition and the advances of technological innovation and renewable energies).

2.3 Cross-sectional climate change sensitivities

Different from the corporate bond literature, which has so far only identified a bond's climate risk exposure using monthly data over longer rolling windows, we calculates a bond's daily exposure to our measures of climate risk to improve the identification of bond price performance in the event of climate risk news shocks. In contrast to monthly returns, daily return data provide sufficient information to detect the abnormal performance of bonds (Bessembinder et al. (2009)). More specifically, we determine each bond's daily sensitivities to the transition and physical risk shocks by estimating the 7-factor model by Chung et al. (2019) over rolling windows of 3 months. Similar to Faccini et al. (2021), the estimation windows are fixed and move forward by one month at each iteration. The following model is run bond-by-bond:

$$\begin{aligned} r_{i,t} = \alpha_{i,t} + \beta_{i,t}^{\prime climate} ClimateShock_t + \beta_{i,t}^{market} r_t^{market} + \beta_{i,t}^{term} Term_t + \beta_{i,t}^{default} Default_t \\ + \beta_{i,t}^{SMB} SMB_t + \beta_{i,t}^{HML} HML_t + \beta_{i,t}^{liquidity} liquidity_t + \beta_{i,t}^{VIX} \Delta VSTOXX_t + \varepsilon_{i,t} \end{aligned} \tag{2}$$

where $r_{i,t}$ is the bond's excess return, $ClimateShock_t$ represents either the transition or physical climate risk shock, r_t^{market}, $Term_t$, $Default_t$, SMB_t, HML_t, $liquidity_t$ and $\Delta VSTOXX_t$ are the bond market factors, including the value-weighted return of the broader corporate bond market, the term spread (i.e. the difference between the monthly value-weighted return in 10-year euro area government bonds and the 1-month OIS rate), the default spread (the difference between the value-weighted returns in euro area 10-year corporate and government bonds), the Small Minus Big (SMB) factor (i.e. the average return of small versus big stock market portfolios), the High Minus Low (HML) factor (i.e. the average return of value versus growth stock market portfolios), the bond liquidity risk factor (i.e. market weighted bid-ask spread) and the market volatility factor (i.e. innovations in the VSTOXX using an AR(1) process), respectively, and the subscripts i and t denote the bond and daily time period.[9,10] As a robustness check, and similar to Huynh and Xia (2021), we also estimate the climate risk betas using the 5-factor model (based on Fama and French (1993); Elton et al. (1995), which excludes the liquidity risk and the market volatility factors. The $\beta_{i,t}^{climate}$ is considered the bond's climate risk beta. By construction, a bond's return reacts positively to an increase in climate change risk shocks when the sign of $\beta_{i,t}^{climate}$ is positive and negatively when the sign of $\beta_{i,t}^{climate}$ is negative. This implies that bonds with a negative exposure to the climate risk shocks provide bad hedges against the risk of climate change.

The final sample includes 3,874 bonds issued by 970 firms. 82% of all observations represent IG bonds, while the remaining 18% are HY bonds. Table 1 shows the descriptive statistics. In total, there are 167,952 bond-month observations for excess price returns. The mean excess return is approximately 0.11% while the median excess return is 0.43%. On average, bonds have a remaining maturity of approximately 5 years, a credit rating of 8 (which translates to BBB+), a face value of 815 million euros and a bid-ask spread of 0.5 percentage points. The standard deviations suggest there is sufficient variation in all variables.

3 Empirical results

We assess the cross-sectional relationship between the bonds' climate risk betas and future returns by first employing univariate portfolio-level analyses and then employing Fama-Macbeth cross-sectional regressions. Following the literature on climate change pricing in risky assets markets, we study the periods before and after the year of the Paris agreement separately. In addition, the analysis separates long-term from short-term bonds since we expect a more pronounced price impact of especially physical risk on bonds with a longer time to maturity.

[9] The time variation in the regression coefficients, denoted by subscript t, is not by unit of time observation. Within the rolling window, coefficients are constant over time.

[10] We do not use the liquidity measure proposed by Bao et al. (2011) – who compute illiquidity as $cov_t(\Delta P_{i,t,d}, \Delta P_{i,t,d+1})$, where $P_{i,t,d}$ is the daily log change in a bond's price at day d – since this measure requires intraday data on transaction prices, which our analysis does not include.

Table 1: Descriptive Statistics

Variables	Source	Obs	Mean	Median	Std Dev	Percentiles			
						5th	25th	75th	95th
Dependent variable									
Excess return (percentage)	Bloomberg	167,952	0.11	0.43	2.65	-4.04	-0.44	1.03	3.08
Climate variables									
Transition risk beta	Author calculations	178,890	-0.0008	-0.0005	0.0225	-0.0235	-0.0044	0.0033	0.0205
Physical risk beta	Author calculations	178,890	-0.0012	-0.0004	0.0247	-0.0301	-0.0048	0.0037	0.0233
Bond characteristics									
Remaining maturity (years)	Bloomberg (ICE BofA)	190,277	5.52	4.79	3.89	1.43	2.99	7.09	11.27
Rating (numerical)	Bloomberg (composite)	190,277	8.04	8	2.52	4	6	9	12
Amount outstanding (millions)	Bloomberg (ICE BofA)	190,277	815.94	750	399.57	387	500	1,000	1,500
Bid-ask spread	Bloomberg	189,983	0.50	0.42	0.43	0.14	0.26	0.63	1.14

Notes: This table shows the summary statistics of the monthly time series. The first variable is the monthly excess return (in percentages), calculated as a bond's price return minus the 1-month OIS rate. The second and third variables are the monthly transition and physical climate risk betas. The last four variables are, at the bond-level, remaining maturity in years, credit rating (average of S&P, Fitch and Moody's) in numerical scores, where 1 refers to AAA and 21 to C, face value in millions of euros and bid-ask spreads, respectively.

Bonds with times to maturities of up to 7 years are classified as short-term, while bonds with longer remaining maturities are considered long-term. Statistically, the conclusions change little when bonds with remaining maturity above 5 years are considered long-term.

3.1 Univariate portfolio-level analysis

We construct the univariate portfolios by sorting individual bonds into quintiles based on their physical or transition risk betas at the end of each month. The portfolios are equal-weighted, but the results look similar when the portfolios are value-weighted using the face values as weights (available upon request). The lowest quintile contains bonds with the lowest betas, while the highest quintile reflects bonds with the highest betas. We also construct a high-minus-low portfolio, which reflects a long position in the lowest portfolios and a short position in the highest portfolios.

Accordingly, for each portfolio, we calculate the 1-month ahead excess return (raw return) and the risk-adjusted return (alphas) using bond and stock market factor models following Fama and French (1993); Elton et al. (1995); Bessembinder et al. (2009). We estimate the 3-factor bond alpha by regressing the future excess portfolio returns on the corporate bond market return, term spread and default spread, and the 6-factor alpha by additionally regressing the excess portfolio returns on the broader stock market return and the SMB and HML stock market factors. In all portfolio tables, the first two columns report the average physical risk beta for the quintile portfolios, while the next columns show the average one-month ahead excess returns and the alphas (in percentages), and the parentheses include Newey and West (1987) adjusted t-statistics.

3.1.1 Physical risk

Table 2 shows portfolios of corporate bonds that are sorted by physical risk betas for the period starting in the year of the Paris agreement, that is from 2015 until September 2021. Results indicate that the future returns on the physical risk portfolios of long-term bonds decrease from 0.92% in the lowest quintile to 0.68%, 0.66% and 0.68% in the third, fourth and fifth quintile, respectively. Accordingly, the difference in future returns on portfolios in the highest and lowest quintile is 0.24%, which is significant at the 5% level. That the return on the portfolios in the two lowest quintiles are significantly higher than the returns on the other portfolios suggests that investors demand higher future returns on portfolios of bonds that are adversely impacted by physical risk shocks (i.e. bonds that have negative physical risk betas). Similarly, the risk-adjusted returns (alphas) from the 3-factor bond and 6-factor bond and stock model of long-term bond portfolios also decrease from the lowest to the highest quintile, albeit monotonically, by -0.79% and -0.84%. These differences are significant at the 1% level. By contrast, the difference between the future returns on portfolios of short-term bonds in the lowest and highest quintile is smaller. Moreover, for short-term bonds, the alphas no longer decrease monotonically from the lowest to highest quintile. While the 3-factor bond and 6-factor alphas in the highest quintiles are significantly lower than in the lowest quintiles of short-term bond portfolios, the high-minus-low differences are more than three times smaller in comparison to the portfolios of long-term bonds, suggesting that physical risk matters less for bonds with shorter maturities.

Table 2: Portfolios sorted by the physical risk beta since the Paris Agreement

Quintiles	Physical risk beta		Future return		3-factor bond alpha		6-factor alpha	
	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Low	-0.0149	-0.0179	0.69	0.92	-0.41	-0.63	-0.43	-0.58
			(6.28)	(4.76)	(-0.64)	(-0.66)	(-0.71)	(-0.68)
2	-0.0025	-0.0033	0.59	0.76	-0.44	-0.83	-0.45	-0.75
			(6.33)	(4.06)	(-1.08)	(-0.99)	(-1.17)	(-1.00)
3	-0.0002	0.0003	0.54	0.68	-0.28	-0.96	-0.29	-0.91
			(7.20)	(3.58)	(-0.77)	(-1.19)	(-0.84)	(-1.22)
4	0.0028	0.0041	0.54	0.66	-0.21	-0.98	-0.23	-0.96
			(6.61)	(3.30)	(-0.54)	(-1.19)	(-0.63)	(-1.23)
High	0.0171	0.0202	0.68	0.68	-0.66	-1.42	-0.66	-1.42
			(4.94)	(2.69)	(-1.04)	(-1.42)	(-1.13)	(-1.48)
High - Low	0.0320	0.0381	-0.01	-0.24**	-0.25***	-0.79***	-0.23***	-0.84***
			(-0.50)	(-2.14)	(-2.93)	(-3.78)	(-2.68)	(-3.60)

Notes: This table shows univariate quintile portfolios of corporate bonds sorted by the physical risk beta. The physical risk beta is estimated using the 7-factor model based on Chung et al. (2019) (see Model 2 in Subsection 3.3). The portfolios are equally weighted. For each portfolio, the table shows the average of the physical risk beta, the 1-month ahead excess price return, and the 3-factor bond and 6-factor alphas. The averages are shown for short- and long-term bonds separately. Bonds with times to maturities of up to 7 years are classified as short-term, while bonds with longer remaining maturities are considered long-term. The data cover the time period from January 2015 until September 2021, after the (anticipation of the) Paris Agreement. The parentheses include Newey and West (1987) adjusted t-statistics. Significance levels are provided for the high-minus-low portfolio: * p<0.1, ** p<0.05, *** p<0.01.

As a robustness check, for the period after 2014, Table 3 sorts corporate bond portfolios by the physical risk beta estimated using the 5-factor instead of the 7-factor model (i.e. excluding the liquidity risk and the market volatility factors from Model 2 in Subsection 3.3). Similar to Table 2, the results show that the future returns on portfolios of long-term bonds in the highest quintile are significantly lower than in the lowest quintile, while there are no significant differences between the returns on portfolios of short-term bonds in the highest and lowest quintiles.

Table 3: Portfolios sorted by the physical risk beta using the alternative 5-factor model

Quintiles	Physical risk beta		Future return		3-factor bond alpha		6-factor alpha	
	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Low	-0.0137	-0.0136	0.70	0.90	-0.57	-0.79	-0.58	-0.75
			(5.84)	(4.52)	(-0.78)	(-0.78)	(-0.84)	(-0.82)
2	-0.0024	-0.0033	0.57	0.73	-0.54	-0.82	-0.55	-0.75
			(5.78)	(4.14)	(-1.11)	(-0.94)	(-1.20)	(-0.96)
3	-0.0002	0.0005	0.54	0.70	-0.30	-0.92	-0.32	-0.89
			(6.98)	(3.71)	(-0.82)	(-1.09)	(-0.89)	(-1.13)
4	0.0019	0.0043	0.56	0.68	-0.14	-1.03	-0.15	-0.97
			(7.36)	(3.40)	(-0.41)	(-1.29)	(-0.47)	(-1.33)
High	0.0169	0.0184	0.67	0.69	-0.44	-1.27	-0.46	-1.26
			(5.30)	(2.66)	(-0.89)	(-1.38)	(-1.00)	(-1.44)
High - Low	0.0306	0.0320	-0.03	-0.21*	0.13	-0.47*	0.12	-0.51**
			(-0.71)	(-1.77)	(0.49)	(-1.84)	(0.48)	(-2.30)

Notes: The physical risk beta is estimated using the 5-factor model based on Fama and French (1993); Elton et al. (1995) (see also Subsection 3.3). The data cover the time period from January 2015 until September 2021, after the (anticipation of the) Paris Agreement. See also the notes to Table 2.

The results look different for the period before the Paris agreement. Table 4 shows the corporate bond portfolios sorted by the physical risk beta for the period from February 2005 until December 2014.[11] The results indicate a non-linear relationship between the average returns across the portfolios. More specifically, for both short- and long-term bonds, the future return and alphas consistently decrease from quintile 1 to quintile 3, while increasing again from quintile 3 to quintile 5. While the (risk-adjusted) returns on the portfolios in the highest quintiles are lower than in the lowest quintiles, the differences are for none of the return estimate significant. Together, consistent with the literature on climate risk pricing, these results suggest there is no significant cross-sectional relationship between physical risk and future corporate bond returns in the period before the Paris agreement.

Table 4: Corporate bond portfolios sorted by the physical risk beta before the Paris Agreement

Quintiles	Physical risk beta		Future return		3-factor bond alpha		6-factor alpha	
	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Low	-0.0339	-0.0465	-0.31	-0.58	0.91	1.62	1.03	1.73
			(-1.54)	(-0.88)	(2.78)	(2.59)	(3.05)	(2.74)
2	-0.0055	-0.0103	-0.58	-0.93	0.48	0.94	0.54	1.04
			(-2.24)	(-1.63)	(3.80)	(3.78)	(4.11)	(4.49)
3	-0.0010	-0.0005	-0.68	-0.94	0.30	0.80	0.35	0.86
			(-2.53)	(-1.76)	(3.42)	(3.99)	(4.11)	(4.92)
4	0.0027	0.0067	-0.67	-0.86	0.32	0.98	0.38	1.06
			(-2.48)	(-1.56)	(2.95)	(3.85)	(3.87)	(4.98)
High	0.0245	0.0323	-0.46	-0.84	0.66	1.10	0.81	1.27
			(-1.92)	(-1.43)	(2.84)	(3.11)	(3.36)	(3.69)
High - Low	0.0584	0.0788	-0.15	-0.26	-0.25	-0.52	-0.22	-0.46
			(-1.20)	(-1.22)	(-1.26)	(-1.41)	(-1.29)	(-1.31)

Notes: The data cover the time period from February 2005 until December 2014, before the (anticipation of the) Paris Agreement. See also the notes to Table 2.

3.1.2 Transition risk

Table 5 reports corporate bond portfolios sorted by transition risk betas for the period from January 2015 until September 2021. The high-minus-low portfolio shows a negative cross-sectional relationship between transition risk and future returns for longer-term bonds after the Paris agreement, but the estimations are insignificant. Furthermore, a closer look at the returns versus the alphas indicates that, while the future returns on the transition risk portfolios of both short- and long-term bonds decreases from the lowest quintile to quintile 3, before increasing again towards the highest quintile, the alphas increase from the lowest quintile to the third or fourth quintile, before significantly decreasing again in the highest quintile.

Table 6 shows that, before 2015, transition risk may to some extent have already been priced in euro area corporate bonds. The results show that both the portfolio returns and alphas decrease from the lowest quintile to the third or fourth quintile. While the returns and alphas increase again from the third or fourth quintiles onwards, the differences between the highest and lowest

[11] Due to the minimum window size of 40 valid return observations in the rolling estimation of the climate risk betas, there are no climate risk betas estimated for January 2005 (see also Subsection 3.3).

Table 5: Corporate bond portfolios sorted by the transition risk beta since the Paris Agreement

Quintiles	Transition risk beta		Future return		3-factor bond alpha		6-factor alpha	
	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Low	-0.0133	-0.0153	0.66	0.84	-0.56	-1.11	-0.59	-1.10
			(5.10)	(3.34)	(-0.82)	(-1.11)	(-0.91)	(-1.19)
2	-0.0023	-0.0035	0.59	0.66	-0.21	-1.07	-0.21	-1.02
			(6.81)	(3.28)	(-0.66)	(-1.30)	(-0.73)	(-1.32)
3	-0.0004	0.0001	0.52	0.64	-0.20	-0.78	-0.21	-0.75
			(7.41)	(3.68)	(-0.62)	(-1.00)	(-0.68)	(-1.00)
4	0.0016	0.0036	0.56	0.76	-0.36	-0.70	-0.37	-0.64
			(6.92)	(4.34)	(-0.78)	(-0.87)	(-0.84)	(-0.87)
High	0.0138	0.0172	0.71	0.80	-0.69	-1.22	-0.69	-1.16
			(5.42)	(3.69)	(-1.04)	(-1.16)	(-1.15)	(-1.23)
High - Low	0.0271	0.0325	0.05	-0.04	-0.13	-0.11	-0.11	-0.06
			(0.99)	(-0.60)	(-1.00)	(-0.29)	(-0.75)	(-0.14)

Notes: This table shows univariate quintile portfolios of corporate bonds sorted by the transition risk beta. The transition risk beta is estimated using the 7-factor model based on Chung et al. (2019) (see Model 2 in Subsection 3.3). The data cover the time period from January 2015 until September 2021, after the (anticipation of the) Paris Agreement. See also the notes to Table 2.

quintiles in the future return and the 6-factor alpha are statistically significant at the 10% level for short-term bonds, suggesting a weak significant cross-sectional relationship between transition risk and the future return of corporate bonds in the period before 2015.

Table 6: Corporate bond portfolios sorted by the transition risk beta before the Paris Agreement

Quintiles	Transition risk beta		Future return		3-factor bond alpha		6-factor alpha	
	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
Low	-0.0256	-0.0360	-0.25	-0.60	0.97	1.58	1.08	1.65
			(-1.43)	(-0.87)	(2.90)	(2.76)	(3.08)	(2.92)
2	-0.0041	-0.0079	-0.60	-0.87	0.46	1.08	0.51	1.12
			(-2.27)	(-1.51)	(3.51)	(3.53)	(3.94)	(3.69)
3	-0.0003	-0.0007	-0.69	-0.91	0.29	0.85	0.36	0.96
			(-2.54)	(-1.69)	(2.79)	(4.20)	(3.56)	(5.92)
4	0.0029	0.0057	-0.65	-0.96	0.36	0.81	0.42	0.93
			(-2.45)	(-1.80)	(3.03)	(3.46)	(4.00)	(4.76)
High	0.0188	0.0264	-0.51	-0.82	0.58	1.12	0.73	1.28
			(-2.03)	(-1.41)	(2.80)	(3.14)	(3.59)	(3.75)
High - Low	0.0444	0.0624	-0.26*	-0.22	-0.40	-0.46	-0.35*	-0.37
			(-1.66)	(-1.24)	(-1.64)	(-1.42)	(-1.76)	(-1.30)

Notes: The data cover the time period from February 2005 until December 2014, before the (anticipation of the) Paris Agreement. See also the notes to Table 5.

3.2 Fama-Macbeth cross-sectional regressions

Our analysis of the cross-sectional relationship between climate risk and future returns at the portfolio-level has the specific advantage of being non-parametric. However, one caveat of analysing portfolios of corporate bonds is that it excludes information at the bond-level and does not control for bond characteristics. We therefore also gauge the relationship between the climate risk betas and future returns at the bond-level using Fama-Macbeth cross-sectional regressions. The following model is estimated:

$$r_{i,t+1} = \alpha_t + \gamma'_{1,t}\beta^{Climate}_{i,t} + \gamma'_{2,t}Controls_{i,t} + \varepsilon_{i,t+1} \tag{3}$$

where $r_{i,t+1}$ is the one-month ahead future excess return, $\beta^{Climate}_{i,t}$ is a vector of the physical and transition risk betas, $Controls_{i,t}$ represents a vector of bond characteristics, including the sensitivity to the broader corporate bond market (i.e. β^{market}_{i}), remaining maturity, rating, outstanding amount (log) and bid-ask spread, and the subscript t denotes the last Friday of each month.[12] Using Model (3), we report the time-series averages of the intercept and the estimated slope coefficients γ'_1 and γ'_2. In parentheses, we include the Fama-Macbeth Newey-West adjusted t-statistics. Bold numbers reflect statistical significance below the 5% level.

3.2.1 Physical risk

Table 7 shows the results of the Fama-Macbeth cross-sectional regressions of the 1-month ahead excess return (in percentages) on the physical risk beta for the period starting in January 2015. The results indicate that the relationship between the physical risk beta and the 1-month ahead returns on both short- and long-term bonds are significantly negative. This suggests that investors demand higher future returns on bonds whose returns are most adversely impacted by physical risk shocks, as reflected by a relatively low physical risk beta. Excluding control variables, the estimated average slopes equal -4.55 and -5.35 for short- and long-term bonds, respectively. The economic magnitude of these effects can be calculated by using the difference between the highest and lowest quintiles in the univariate portfolio analysis in Table 2. Table 2 reports a high-minus-low difference in the physical risk beta of 0.032 and 0.038 for short- and long-term bonds, respectively. Multiplying these differences with the average slope coefficients suggests a physical risk premium of 15 and 20 basis points for short- and long-term bonds, respectively. The significant cross-sectional relationship between the physical risk beta and future returns holds for when bond characteristics are controlled for, albeit their economic magnitude reduces to 14 for short-term bonds and 15 basis points for long-term bonds.

The results of the Fama-Macbeth regressions confirm the finding that long-term bonds in

[12] The time period refers to the last Friday instead of the last working day of each month, as end-of-month portfolio reallocations can impact prices. When there is no trading on the respective Friday, then we take the last trading day prior to the last Friday of each month as the end-of-month date.

portfolios with a relatively low physical risk beta have a higher expected return (Table 2 reports the high-minus-low difference in future returns equals 24 basis points for long-term bonds, which is close to the economic magnitude estimated by the Fama-Macbeth regressions). In addition, the Fama-McBeth analysis also indicates that the future return on short-term bonds may be significantly impacted by physical risk. By contrast, the results of the portfolio analysis in Table 2 indicate that the future returns on short-term bonds reduce consistently from the lowest to the fourth quintile, before increasing again from the fourth to the highest quintile. Accordingly, the estimation of cross-sectional Fama-Macbeth regressions does not capture this non-linearity.

Table 7: Fama-Macbeth cross-sectional regressions for the period after the Paris agreement

Maturity bucket	Intercept	Physical	β^{market}	Rating	Maturity	Value	bid-ask	Adj. R-sqr
Short-term	**0.59**	**-4.55**						0.03
	(6.89)	(2.17)						
Short-term	-0.69	**-4.25**	0.00	0.01	0.00	0.05	**0.27**	0.26
	(1.16)	(2.58)	(0.01)	(0.81)	(1.34)	(1.76)	(2.08)	
Long-term	**0.73**	**-5.35**						0.05
	(4.24)	(2.16)						
Long-term	0.14	**-3.89**	-0.01	0.02	0.00	0.01	0.19	0.29
	(0.17)	(2.29)	(0.43)	(1.11)	(0.38)	(0.35)	(1.74)	

Notes: This table shows average intercepts and slope coefficients estimated using Fama-Macbeth cross-sectional regressions. The dependent variable is the 1-month ahead excess price return in percentages (not decimals). Newey-West adjusted t-statistics are included in the parentheses. The data cover the time period from January 2015 until September 2021, after the (anticipation of the) Paris Agreement. Bold numbers reflect statistical significance below the 5% level.

The portfolio analysis and Fama-Macbeth regressions together suggest that investors demand higher returns on long-term bonds that are prone to physical risk. To gauge whether investors continue to demand higher returns further into the future, we additionally employ Fama-Macbeth regressions of the accumulated monthly sum of a bond's excess return - $\sum_{h=0}^{H} r_{i,t+h}$ for H = 1, 2, ..., 6 - on the right-hand side of equation 3 for the period starting in January 2015. Using the accumluated sum of returns, we determine the persistence of the intertemporal relationship between the physical risk beta and excess price returns of long-term bonds.

Figure 3 shows the results for when the control variables are included. Two observations stand out. First, the physical risk premium of long-term bonds increases from 15 basis points 1-month ahead to 34 basis points 2-months ahead, suggesting the impact of physical risk on corporate bond pricing becomes more pronounced over time. Second, the intertemporal relationship between the physical risk beta and excess returns of long-term bonds persists, with the physical risk premium continuing to stand at 34 basis points 6 months ahead.

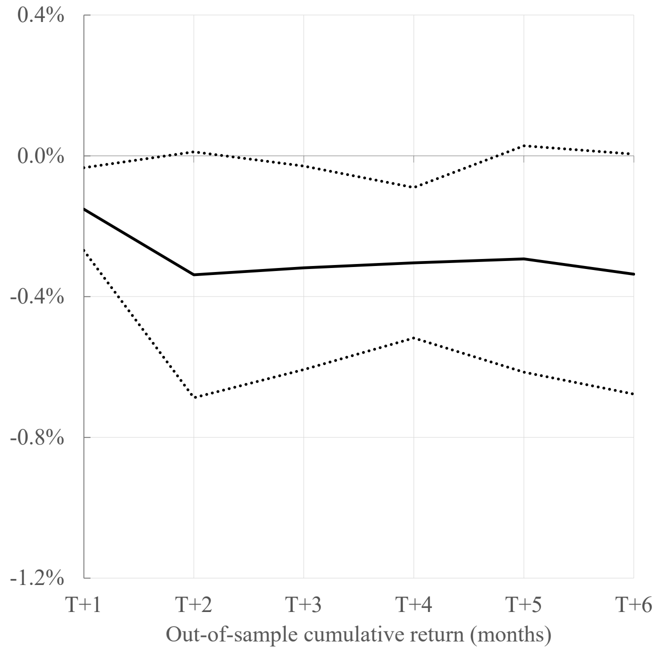


Figure 3: Cumulative returns of long-term bonds regressed on physical risk beta after Paris agreement

Notes: This figure shows the results of Fama-Macbeth cross-sectional regressions of the future cumulative excess returns of long-term bonds. To facilitate the economic interpretation of the results, the y-axes show the average Fama-Macbeth slope coefficients multiplied by the differences in the average physical risk beta between lowest and highest portfolios (0.038; see Table 2). The data cover the time period from January 2015 until September 2021, after the (anticipation of the) Paris Agreement. The dotted lines represent the 90% confidence intervals using Newey-West adjusted standard errors.

Table 8 reports the results of the Fama-Macbeth regressions of the 1-month ahead excess return on the physical risk beta for the period from February 2005 until December 2014. The results confirm the finding of the portfolio analysis that for long-term bonds there exists no significant relationship between the physical risk beta and future return. However, the cross-sectional relationship between the physical risk beta and the future return of bonds with short-term maturities is found significant with a average slope of -2.38 when excluding control variables. Using the high-minus-low difference in future return from the portfolio analysis in Table 2, we calculate the physical risk premium to amount to 8 basis points for short-term bonds before the Paris agreement. When including the control variables, the physical risk premium is estimated to be 7 basis points, but the relationship is no longer significant at the 5% but at the 10% level.

Table 8: Fama-Macbeth cross-sectional regressions for the period before the Paris agreement

Maturity bucket	Intercept	Physical	β^{market}	Rating	Maturity	Value	bid-ask	Adj. R-sqr
Short-term	**-1.11**	**-2.38**						0.02
	(2.10)	(2.16)						
Short-term	**-2.38**	-2.16	0.13	0.02	0.00	0.04	0.15	0.24
	(3.65)	(1.80)	(1.76)	(1.15)	(1.37)	(1.37)	(0.80)	
Long-term	-0.98	0.12						0.04
	(1.52)	(0.07)						
Long-term	-2.21	-0.68	0.05	0.04	0.00	0.04	-0.06	0.21
	(1.71)	(0.43)	(1.24)	(1.49)	(0.33)	(0.87)	(0.41)	

Notes: The data cover the time period from February 2005 until December 2014, before the (anticipation of the) Paris Agreement. See also the notes to Table 7.

3.2.2 Transition risk

Table 9 and Table 10 show the results of the Fama-Macbeth regressions of the 1-month ahead excess return on the transition risk beta for the period before January 2015 and after December 2014, respectively. The results confirm the findings from the portfolio analysis and indicate a negative but insignificant relationship between transition risk and future returns on both short- and long-term bonds. Together, the results of the portfolio analysis and the Fama-Macbeth cross-sectional regressions suggests a stronger and more significant pricing in of physical than transition risk in euro area corporate bond markets.

Table 9: Fama-Macbeth cross-sectional regressions for the period after the Paris agreement

Maturity bucket	Intercept	Transition	β^{market}	Rating	Maturity	Value	bid-ask	Adj. R-sqr
Short-term	**0.59**	-0.48						0.03
	(6.70)	(0.23)						
Short-term	-0.73	-1.07	-0.01	0.01	0.00	0.05	**0.26**	0.25
	(1.23)	(0.58)	(0.43)	(0.96)	(1.59)	(1.82)	(2.06)	
Long-term	**0.72**	-0.36						0.06
	(4.10)	(0.15)						
Long-term	0.26	-2.15	-0.01	0.01	0.00	0.01	0.18	0.29
	(0.27)	(1.11)	(0.47)	(0.70)	(0.30)	(0.24)	(1.71)	

Notes: The data cover the time period from January 2015 until September 2021, after the (anticipation of the) Paris Agreement. See also the notes to Table 7.

Table 10: Fama-Macbeth cross-sectional regressions for the period before the Paris agreement

Maturity bucket	Intercept	Transition	β^{market}	Rating	Maturity	Value	bid-ask	Adj. R-sqr
Short-term	**-1.11**	-3.36						0.03
	(2.12)	(1.39)						
Short-term	**-2.36**	-1.99	**0.16**	0.01	0.00	0.04	0.16	0.25
	(3.97)	(1.33)	(2.26)	(0.76)	(1.20)	(1.54)	(0.86)	
Long-term	-0.96	-2.28						0.04
	(1.50)	(0.85)						
Long-term	-1.77	-1.42	0.07	0.04	0.00	0.02	-0.06	0.21
	(1.40)	(0.72)	(1.76)	(1.38)	(0.23)	(0.53)	(0.46)	

Notes: The data cover the time period from February 2005 until December 2014, before the (anticipation of the) Paris Agreement. See also the notes to Table 7.

4 Conclusion

We present estimates of physical and transition risk premiums in euro area corporate bond markets using two novel text-based climate risk indicators. We contribute to the literature by analysing the extent to which climate risk premiums in corporate bond markets reflect physical or transition risk. In addition, we are the first to map the pricing effects of climate risk in euro area corporate bond markets. Focusing on the euro area is important for two reasons. First, market-based debt is a more important source of finance for European than for American corporations. Second, the European Union plays a prominent role in climate regulations initiatives, as reflected by the adoption of a self-climate regulation, and its commitment to becoming the first net-zero emissions continent.

Different from earlier studies on climate risk pricing in corporate bonds, we improve identification by employing portfolio analysis and Fama-Macbeth cross-sectional regressions using daily instead of monthly data on climate risk shocks and bond prices. Our findings show that physical risk is significantly priced in euro area corporate bonds with longer-term maturities since the anticipation of the Paris agreement. Physical risk is also priced in short-term bonds, but the premium is smaller and less significant. Accounting for bond characteristics, the physical risk premium for long-term bonds is negative and estimated to be 15 basis points 1-month ahead and 34 basis points 2- to 6-months ahead. The negative physical risk premium mostly reflects investors demanding higher future returns on bonds that are bad hedges against physical risk. Similar to the findings in the stock market literature, corporate bonds did not contain significant physical risk premiums before 2015, indicating that investors' incentives to hedge against physical risk intensified after the Paris agreement. By contrast, there is no strong evidence for transition risk premiums in euro area corporate bond markets.

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