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Review

# Climate change, risk factors and stock returns: A review of the literature[☆]

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ABSTRACT

This article reviews how climate change could be considered an additional source of market risk. I discuss the types of data needed to analyse the climate risk drivers that shape the dynamics of the equity market. I present empirical evidence at both the macro and micro-level, analysing whether and to what extent the equity market prices climate change and related risks. Top-down and bottom-up approaches are compared to understand which climate risk is more likely to affect the cross-section of stock returns, both within and across sectors. Emphasis is also placed on investors' beliefs about climate change risks, and the related asset pricing implications are analysed. I conclude by illustrating further directions for both empirical and theoretical research in the field of climate finance.

## 1. Introduction

Climate change is shaping the sociological, geopolitical and financial dynamics of our time. The stark impact of sociological issues may be affected by changes in long-term climate variable patterns, with possible effects on food shortage and migration, particularly in developing countries (Dell et al., 2012). Geopolitical bargaining marking the path to a new green economy will result from a mixture of diplomatic scenarios that might dictate radical changes in our societies. Financial markets will also play a crucial role, as the shift to a green economy will also depend on monetary flows provided by governments and investors for such a metamorphosis (NGFS, 2020).

Although the scientific community has found that most of the climate change and related effects will be more evident in the future, some environmental and policy implications can already be seen today. For instance, in 2018, the first bankruptcy 'because of climate change' occurred in the US.[1] Moreover, McGlade and Ekins (2015) have argued that one-third of oil reserves, one half of gas reserves and 80% of coal reserves must remain unburned from 2010 to 2050 to meet the target of 2° warming set by the Paris Agreement. Similar results have been found in other studies, raising concerns about the serious threat of certain assets becoming 'stranded' (Semieniuk et al., 2021).[2]

These data are of interest for governments, which could be responsible for the coverage of public costs because of physical and transitional damages (Lamperti et al., 2019), and for financial actors as well. According to the Centre for the Study of Financial Innovation survey, climate change was ranked in 2019 as the second-highest risk factor for reinsurance companies and the third for non-life insurance firms.[3] Moreover, recent surveys have argued that these concerns also apply to banks and institutional investors (Amel-Zadeh, 2021; CFA, 2020; Krueger et al., 2020). Thus, if the world will not prepare itself to face (or at least *mitigate*) one of the most important challenges of this century, economic damages and social concerns will inevitably increase in the coming years.

These empirical facts can explain the 'momentum' climate change has recently gained in scientific debates and the consequent political efforts to concentrate the world's attention on this global issue. One of the most important events in this direction was the Conference of the Parties 21 (or Paris Agreement). Beyond the strict targets set for each country at an international level, finance played an important role in the agreement. In particular, the second article of the Paris Agreement expresses its goal of '*making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development*'.[4]

The financial world seems to have accepted this challenge with efforts from policymakers[5], practitioners and academics, although the

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[1] https://www.wsj.com/articles/pg-e-wildfires-and-the-first-climate-change-bankruptcy-11547820006.

[2] For a full review on this point, the reader is referred to Curtin et al. (2019).

[3] https://www.csfi.org/insurance-banana-skins.

[4] https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf.

[5] Notably, several new institutions, organisation and initiatives emerged after the Paris Agreement; for instance, the Task Force on Climate-related Financial Disclosures (TFCD) and the Network for Greening the Financial System (NGFS) were both established after the agreement. To understand the overwhelming climate-related regulatory framework in the financial system, Feridun and Gungor (2020) wrote an interesting review with a focus on the banking sector.

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latter has been considered '*late to the game*' in recent years (Diaz-Rainey et al., 2017; Hong et al., 2020). Engagement with the financial industry, combined with the award of 2018's Nobel Prize in Economics to William Nordhaus (for his contributions on integrated assessment models for long-run macroeconomic analysis (Nordhaus, 1977, 1993)) laid the ground for the validation of a new kind of literature, called *climate finance* (Hong et al., 2020). Climate finance emerged from the interconnections between environmental and financial economics (Giglio et al., 2020).

Two main currents characterise the literature on climate finance. The first relates to climate change science and the related risks. The second describes the financial consequences of climate change for asset pricing.

Climate change risks can be divided into physical and transitional risks (Carney, 2015). Physical risks refer to the mainly negative impact of climate and weather-related events on company operations, society and supply chains (Tankov & Tantet, 2019). There are two types of physical risk: acute and chronic. Acute physical risks are related to *extreme weather events*, such as floods, extreme drought, wildfires, hurricanes and heatwaves. Chronic climate risks represent *slowly* evolving phenomena, such as sea-level rise, changes in precipitation patterns and temperature rise. On the other hand, transitional risks refer to all the possible scenarios coherent with a path to a low-carbon economy and all related implications for fossil fuels and dependent sectors (Curtin et al., 2019). Firm reputation and technology changes represent other transitional risks as well (Semieniuk et al., 2021). This review focuses on both types of climate change risks, and I discuss how their dynamics matter for asset pricing.

With respect to the financial side, climate finance literature can be divided according to the type of financial risk and asset analysed, as well as the relative methodology applied. Recent studies have found that climate change could affect different types of financial risks. In particular, studies in climate finance showed that climate change could affect (i) credit (Painter, 2020); (ii) underwriting (NGFS, 2020); (iii) operational and (iv) market risks. In this review, I survey the implications of climate change for market risks. Among several assets whose market value may be exposed to physical risks, such as real estate (Baldauf et al., 2020; Bernstein et al., 2019; Giglio et al., 2021; Murfin & Spiegel, 2020), municipal bonds (Bourdeau-Brien & Kryzanowski, 2020; Goldsmith-Pinkham et al., 2021; Painter, 2020), and derivatives (Kruttli et al., 2021; Schlenker & Taylor, 2021), in this review, I concentrate on the stock market. However, given the novelty of the field, findings with respect to other asset classes are integrated to foster the comprehension of certain results observed in the literature. Finally, empirical research that focuses on how climate risks are measured in financial portfolios can be divided between top-down and bottom-up approaches. In this survey, both methodologies are analysed to review how stock prices interact with climate change dynamics.

This article makes several contributions to the climate finance literature. First, to the best of my knowledge, it is the first work to focus on both top-down and bottom-up approaches to explain how climate risks should affect the cross-section of stock returns. Combining these two approaches is important to examine the possible hedging (Engle et al., 2020) and climate mitigation opportunities (Azar et al., 2021) the financial market can provide against climate change risks. Second, this article also contributes to the recent debates about stock market inefficiency in pricing climate change risks. Although most of these works provide theoretical argumentations (Ameli et al., 2020; Semieniuk et al., 2021; Thomä & Chenet, 2017), this review describes the quantitative implications of climate finance studies, detailing possible rational and behavioural reasons for observed results.

The rest of the work is organised as follows. Section 2 discusses the types of data needed to analyse how the physical and transition risk channels can affect the equity market. In Sections 3 and 4, I review how these channels are modelled at the top-down and bottom-up levels, respectively, and how these risks may affect the cross-section of stock returns. Finally, Section 5 concludes this work, addressing current gaps in the literature and possible future research avenues in climate finance.

## 2. Modelling climate risks in the equity market: The physical and transition risk channels

This section reviews how firm value can be affected by either the physical or the transition risk channels. Additionally, I discuss the types of data needed to build measures that proxy for these climate risk drivers and how these measures can be related to firm-level variables. Fig. 1 presents an overview of the different physical and transition risk drivers as well as the macro-categories of data needed to model climate risks in the equity market.

At the more fundamental level, physical risks depend on the following three drivers (Tankov & Tantet, 2019):

$$\text{Physical risk} = f(\text{hazard, exposure, vulnerability}) \tag{1}$$

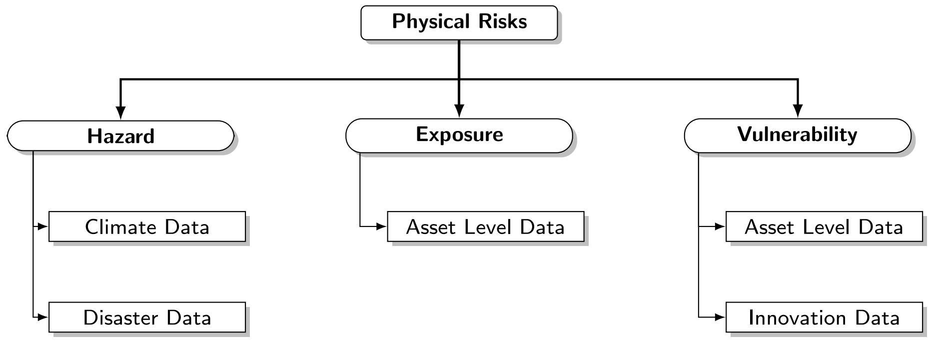
The variable *hazard* refers to climate events or weather patterns of interest, both in terms of physical intensity and in probability of occurrence. The term *exposure* represents the geographical distribution of the entity or system that the climate hazard might impact, and the variable *vulnerability* refers to the threats (such as fragilities or predispositions) to the asset from of its exposure to the climate hazard. Each term in Eq. (1) requires specific and geo-spatial data to adapt the analysis to the particular entity of interest.

The term *hazard* in Eq. (1) can be analysed using two different types of datasets, namely climate and natural disasters datasets. Regarding the former, Tankov and Tantet (2019) classified four different types of climate datasets for modelling physical risks. This classification ranks climate datasets according to the levels of modelling required to create them, distinguishing between (i) observational datasets, (ii) reanalyses datasets, (iii) projections datasets and (iv) climate indices. Observational datasets can be further divided into (i) situ observations (such as weather stations) and (ii) teledetection from the ground or from space. In the latter case, the observational dataset is created by means of satellite data. A full review of each these datasets would be beyond the scope of this review. Interested readers are referred to the work of Tankov and Tantet (2019) for a more comprehensive discussion about these climate data. In this work, I describe how these datasets have been used in studies analysing the stock market and the sources to gather these kinds of data.

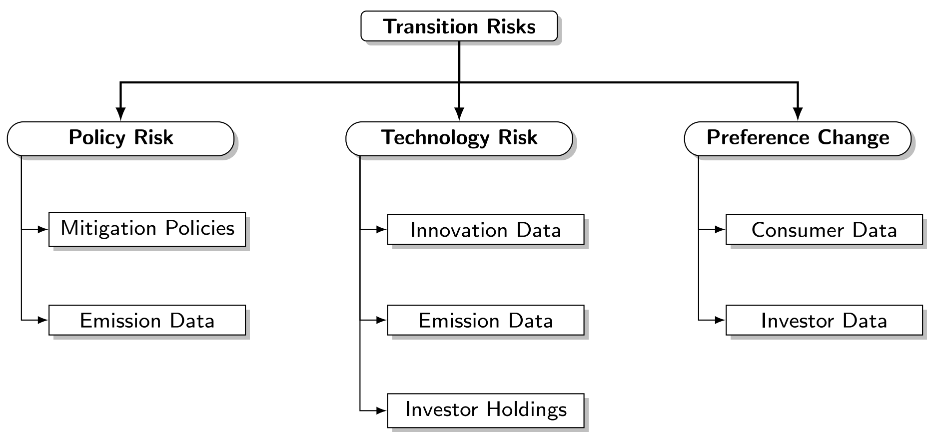
Although traditionally used in disaster risk management (Doktycz & Abkowitz, 2019), natural disaster datasets are gaining momentum in climate finance. Natural hazards can be divided into (i) hydrological (e.g. floods and mass movements), (ii) meteorological (e.g. storms and tropical cyclones), (iii) climatological (e.g. heatwaves and droughts) and (iv) geophysical (e.g. earthquakes and volcanic eruptions) disasters. Natural disaster datasets are attractive in climate finance because, unlike climate datasets, they provide both the location and the historical economic damages of a certain physical hazard. Notably, the criteria under which a certain natural hazard is accounted for in a specific database may differ across data providers (Doktycz & Abkowitz, 2019).

The quantitative assessment at the firm level of the other two variables in Eq. (1) requires the use of asset-level data. The latter represents any type of quantitative or qualitative information regarding physical assets, including their characteristics, geographical locations and ownership (Preudhomme & Mazzacurati, 2020). Moreover, the level of a firm's vulnerability to physical risks is negatively related to its adaptation capacity. Thus, modelling this channel further requires data geared toward firm innovation, such as research and development (R&D) expenditures and firm patents.

The choice of a framework to categorise transitional risks is less canonical than the one discussed for physical risks. Nevertheless, Semieniuk et al. (2021) provided a taxonomy that allows one to identify several transition risk drivers that may lead to economic impacts in financial markets. This review describes how the transition risks discussed in Semieniuk et al. (2021) can affect the equity market.




**(a)** Types of data needed to model physical risks in the equity market.




**(b)** Types of data needed to model transition risks in the equity market.

**Fig. 1.** Types of data needed to model climate change risks in the equity market.

Transition risks are a combination of three factors (Semieniuk et al., 2021):

$$\text{Transitional risk} = f(\text{policy risk, technology risk, preference change}) \tag{2}$$

The term *policy risk* in Eq. (2) refers to the risks and opportunities that may be triggered by climate mitigation policies. The aim of these policies is to reduce the amount of greenhouse gas (GHG) emissions in the atmosphere, especially carbon dioxide ($CO_2$) emissions. The reason for mitigations policies to focus on $CO_2$ emissions is that these kinds of emissions are considered the primary factor in human-induced global warming (Nordhaus, 1977, 1993). Climate mitigation policies can be implemented via market-based and non-marked-based mechanisms. Market-based mechanisms comprise the two forms of carbon pricing (Metcalf, 2009): (i) carbon taxes and (ii) cap-and-trade schemes. Non-market-based mechanisms are related to (i) environmental regulation; (ii) green subsidies; and (iii) voluntary commitments by government and firms (Bolton & Kacperczyk, 2021b).

The Greenhouse Gas Protocol sets the standards for quantify corporate emissions at the firm level, distinguishing between three different sources of GHG emissions.[6] Scope 1 emissions refer to the direct emissions from plants owned or controlled by a company. Scope 2 and scope 3 emissions represent two forms of indirect emissions. In particular, scope 2 emissions arise from the generation of purchased steam, heat, and electricity consumed by the firm, while scope 3 emissions come from sources not owned or controlled by the company, such as emissions from outsourced activities. Studies in climate finance tend to assume that the higher a company's scope emissions, the 'browner' that firm is (Bolton & Kacperczyk, 2021a). The opposite holds for 'green' firms. Moreover, given these sources of scope emissions, three different measures at the plant (Akey & Appel, 2021) or firm level (Hsu et al., 2020) can be derived. The first is the total level of emissions, that may be decomposed for each type of scope emission subcategory. Year-by-year change in emissions quantifies the growth rate in annual corporate emissions. Finally, one could also compute an emission intensity measure, quantifying carbon emissions per unit of sales (Bolton & Kacperczyk, 2021a) or assets (Hsu et al., 2020). Each of these measures can be used to estimate the degree of exposure a company may have to different climate mitigation policies (Bolton & Kacperczyk, 2021a).

The variable *technology risk* in Eq. (2) refers to the introduction of cost-saving technologies that would foster the adoption of low-carbon energy sources. Notably, society is still reliant on fossil fuel energies, which in 2020 accounted for more than 80% of energy supply (Rapier, 2020). However, several factors may be pushing firms to adopt low-carbon energy sources, such as expected liabilities toward environmental policies (Chu et al., 2020), investor pressure (Azar et al., 2021), or simply to maintain competition in the market (Trinks et al., 2020). Thus, modelling technology risk requires firm-level information about (i) innovation data, such as abatement costs (Akey & Appel, 2021), R&D expenditures, and firm patents aimed to curb firm emissions (Chu et al., 2020); (ii) emission data; and (iii) investor holdings. The latter kind of data allows the researcher to analyse whether corporate governance could affect the carbon management practices of targeted firms. From the motivations that could trigger firms to adopt carbon management practices, it is clear that the variables *policy risk* and *technology risk* in Eq. (2) are closely interlinked.

[6] See https://ghgprotocol.org/.

Finally, the term *preference change* in Eq. (2) may be related to two non-mutually exclusive channels (Pástor et al., 2020). The first refers to unexpected preference changes in green-motivated costumers' tastes. This group's environmental concerns may positively affect the cash flows of green firms. The consumer channel may be modelled (i) directly, gathering data from consumer surveys (Ricci & Banterle, 2020) or about firm profitability (Dai et al., 2021); or (ii) indirectly, examining changes in analysts' earnings revisions for green firms (Ramelli et al., 2021). The second channel is represented by unexpected shifts in investor preferences toward carbon-intensive assets. Investors may change their preferences regarding these assets for both pecuniary and nonpecuniary motives. In the former case, the financial logic is tied to risk–return considerations, as carbon assets may be deemed to have a higher downside risk (Ilhan et al., 2021b). On the other hand, nonpecuniary motives are related to the ethical benefits an investor derives when holding climate-friendly assets (Fama & French, 2007). Modelling the investor channel requires data about (i) investor surveys (Krueger et al., 2020); or (ii) financial flows toward green labelled funds (Ceccarelli et al., 2019).

Clearly, physical and transitional risks are interlinked. This phenomenon is particularly true for studies attempting to analyse the evolution of *future* physical risk damages, which use projection datasets (Dietz et al., 2016). In these types of analyses, one of the main sources of uncertainty is the future amount of $CO_2$ concentration in the atmosphere (Tankov & Tantet, 2019). The value of this figure, in turn, will depend upon the effectiveness of climate mitigation policies adopted in the following years (Semieniuk et al., 2021).

## 3. Top-down approaches: Climate risks in investment portfolios

The aim of this article is to explain how the climate risk drivers described in Section 2 should affect the cross-section of stock returns. Analysing how climate risks may systematically affect the equity market pose several modelling challenges for the field of asset pricing. In recent years, however, the climate finance literature has identified two ways to link the dynamics described in Eqs. (1) and (2) to equity prices at the top-down level.

According to Giglio et al. (2020), financial research that models climate risks in macro financial asset pricing models can be divided according to the researcher's beliefs about climate change uncertainty. It remains an open debate whether climate risks represent a low probability outcome resulting in a 'disaster' (Weitzman, 2009) or a stochastic process dependent on today's aggregate consumption (Nordhaus, 1977). One of the main goals of these models is the computation of the social cost of carbon (Bansal et al., 2019; Barnett et al., 2020; Daniel et al., 2016), the value of which has important sociological and policy implications.[7] Although initial estimates of this measure primarily relied on macroeconomic theories, Bansal et al. (2019) and Balvers et al. (2017) argued that the equity market might provide an independent judgement of current future climate change risks. Therefore, empirical evidence on this point can drive climate finance research toward better construction of macro-financial models, and in turn, better estimates of the social cost of carbon.

Other approaches tend to develop theoretical equilibrium models aimed to align environmental, social and corporate governance (ESG) criteria with asset return dynamics (Avramov et al., 2021; Pástor et al., 2020; Pedersen et al., 2020). As discussed in this review, ESG investing is strictly related to climate change considerations by investors (Engle et al., 2020; Pástor et al., 2021). Although some of these models tend to consider the indirect effects that investor preferences toward sustainability may have on asset prices, Pástor et al. (2020) developed a model where climate risks are allowed to determine equilibrium returns, as they enter directly in the investors' utility functions.

For both of these approaches, the theoretical predictions ultimately rest on how and whether financial markets *price* these risks. The climate finance literature analysing the equity market infers this kind of information through reliance on the results obtained by empirical asset pricing tests of security returns. Thus, in the next subsection, empirical evidence from the application of factor models is reviewed to demonstrate how equity prices are historically related to climate change dynamics.

### 3.1. Factor models and climate change risks: An open debate

Grounded in a solid academic background, factor models provide a general framework to analyse the systematic drivers to explain the cross-section of asset returns. *Linear* factor models represent a special case of the arbitrage pricing theory (Ross, 1976), and assume that the return of an asset can be modelled as a combination of underlying risk factors:

$$r_{t,i} = \alpha_i + \sum_{k=1}^{K} \beta_{k,i} f_{k,t} + \varepsilon_{t,i} \tag{3}$$

Suppose factors other than the market portfolio can explain the cross-section of asset returns. In that case, these factors are called *anomalies*, as they are in contradiction with the mean–variance efficiency assumptions of the capital asset pricing model (Sharpe, 1964), and in general, with the (semi-strong) form of efficient market hypothesis (Fama, 1970). Early work in this direction was pioneered by Fama and French (1992) and Fama and French (1993).

Studies in climate finance that employ factor models to analyse the cross-section of stock returns tend to rely on portfolio sorts rather than single stocks, justifying this assumption in light of more stable beta estimations (Petersen, 2009). Hence, Eq. (3) becomes

$$r_{t,p} = \alpha_p + \sum_{k=1}^{K} \beta_{p,k} f_{t,k} + \varepsilon_{t,p} \tag{4}$$

whose variance, under the assumption of factor models, is defined as

$$\sigma_p^2 = \sum_{k=1}^{K} \beta_{p,k}^2 \sigma_k^2 + \sigma_{\varepsilon,p}^2. \tag{5}$$

Thus, reasoning in terms of portfolio, the fundamental debate in climate finance is to understand whether climate change risk dynamics enter in Eqs. (4) and (5) as parameters $\alpha_p$, $\beta_{p,k}$ or $\sigma_{\varepsilon,p}^2$. In other words, it is still an open question whether climate risks represent an anomaly, an extra source of market risk priced in the financial market or instead of a firm-specific characteristic that investors could eliminate through diversification. Considered alone, these results make it difficult for a researcher to discern how climate risks should affect equilibrium asset returns.

Given the contradictory results observed in the literature, Eq. (4) will be assessed sequentially to compare the data, assumptions and empirical results for each study presented more qualitatively. Thus, the discussion begins with the data used to construct the climate risk measures aimed to proxy for the physical and transition risk channels in Eqs. (1) and (2), respectively. I then describe the underlying economic rationale provided by studies in climate finance to link portfolio returns to the climate risk measures. Finally, I discuss the asset pricing implications resulting from empirical evidence of climate risk pricing in the equity market. Table 1 summarises the climate risk factors and the economic rationale and the findings for each study presented.

[7] The social cost of carbon is a critical ingredient of carbon pricing policies to tackle climate change risks, as it measures the present value of the damage done by emitting an additional ton of $CO_2$ emissions (Nordhaus, 1977). Different assumptions in macro-financial models may imply different estimations of this measure.

**Table 1**
Climate risk factors and the cross-section of stock returns.

| Study | Climate risk measure | Economic rationale | Countries | Sectors | Period | Sample | Is climate risk priced? |
|---|---|---|---|---|---|---|---|
| Balvers et al. (2017) | Shocks in temperature | Sector and firm dynamics | USA | Multiple | 1953–2015 | n.a. | |
| Bansal et al. (2019) | Temperature anomaly | Dividend beta | USA | Multiple | 1970–2016 | n.a. | |
| Bolton and Kacperczyk (2021a) | Three emission measures | Transition risk proxies | USA | Multiple | 2005–2017 | 3421 | |
| Bolton and Kacperczyk (2020) | Three emission measures | Transition risk proxies | 77 countries | Multiple | 2005–2018 | 14,400 | Yes |
| Engle et al. (2020) | E-scores | Hedging assets | USA | Multiple | 2009–2016 | n.a. | |
| Hsu et al. (2020) | Emission intensity | Climate policy risk | USA | Multiple | 1991–2016 | 503 | |
| Nagar and Schoenfeld (2021) | Text mining index | Economic tracking | USA | Multiple | 2003–2019 | 10,000 | |
| Ardia et al. (2021) | Emission intensity | Pástor et al. (2020) | USA | Multiple | 2010–2018 | 500 | |
| Cheema-Fox et al. (2021) | Two emission measures | Investor irrationality | USA | Multiple | 2013–2020 | 1002 | |
| Ding et al. (2020) | Soil moisture data | Forecast of firm profit | Multiple | Food | 1984–2014 | 776 | |
| Görgen et al. (2020) | BG scores | Transition risk proxies | Multiple | Multiple | 2010–2017 | 1657 | |
| Gostlow (2019) | FTS scores | Climate risk proxies | USA, EU and Japan | Multiple | 2008–2017 | 668 | No |
| Hong et al. (2019) | PDSI index | Forecast of firm profit | 31 Countries | Food | 1985–2014 | 776 | |
| In et al. (2017) | Emission intensity | Investor irrationality | USA | Multiple | 2005–2015 | 739 | |
| Jiang and Weng (2019) | ACI index | Forecast of firm profit | USA and Canada | Food and forestry | 1993–2018 | 145 | |
| Kumar et al. (2019) | Temperature anomaly | Forecast of firm profit | USA | Multiple | 1926–2016 | n.a. | |
| Pástor et al. (2021) | E-scores | Pástor et al. (2020) | USA | Multiple | 2012–2020 | n.a. | |

#### 3.1.1. *Data and methods to construct the climate change risk proxies*

In order to construct the climate risk factor of interest, one needs first to determine the climate risk proxy at the firm or portfolio level. In this subsection, I review the different kinds of datasets and methodologies used to construct proxies of climate risks at the top-down level.

With respect to physical risk measures, Table 1 shows the types of measures used to proxy for the term *hazard* in Eq. (1). Temperature anomalies are the most used variable, with droughts coming in second.[8] The high availability of weather stations worldwide makes this kind of observational data the most natural way to include temperature anomalies in Eq. (4). Given that this subset of studies in Table 1 analysed the US stock market, the data for the temperature time series were mostly retrieved from the U.S. National Climatic Data Center. The temperature beta can be estimated using either the return sensitivity of stocks to the abnormal changes at the monthly (Kumar et al., 2019); annual (Balvers et al., 2017); or quinquennial (Bansal et al., 2019) temperature levels. In the latter case, the aim in Bansal et al. (2019) was to allow the temperature beta to reflect risks related to the economic effects of global warming rather than short-run fluctuations in weather.

Drought measures were proxied by using both climate indices and observational datasets. Regarding the former, climate indices such as the Palmer Drought Severity Index (PDSI) and the Actuaries Climate Index (ACI) are a promising way for tracking over time physical hazards that may not be directly described by a specific climate variable (Tankov & Tantet, 2019). On the other hand, Ding et al. (2020) asserted that satellite data usage provides a more reliable way to quantify such time-series variation, as observational datasets are less dependent on measurement error problems than climate indices. Nevertheless, the drought risk proxy among these studies tends to be similar, and the approach demonstrated in Hong et al. (2019) is used as a reference in the literature. Specifically, taking the PDSI index as a standard, one may estimate the long-term drought *trend* at a certain location $i$, up to a certain year $t$, via the equation

$$PDSI_{i,t} = a_i + b_i t + c_i PDSI_{i,t-1} + \epsilon_{i,t}. \tag{6}$$

The parameter of interest in Eq. (6) is $b_i$, which can be considered the long-term effect of climate change on a country's drought vulnerability. It is important to understand how the parameter $b_i$ in Eq. (6) is related to the variables *exposure* and *vulnerability* in Eq. (1). Generally, studies in climate finance that employ top-down approaches tend to proxy the term exposure in Eq. (1) using the countries where firm headquarters are located (Jiang & Weng, 2019). However, the facilities of listed firms (such as establishments and branches) may be spread heterogeneously worldwide, and they may feature different levels of profitability within the country where the company headquarters are located (Hugon & Law, 2019). The quality of the above assumption then critically depends on the firm characteristics in the sample under investigation. Hong et al. (2019) found that in most of the countries, the food industries were formed by small to medium-sized enterprises (SMEs). Thus, the profitability of these companies could be more vulnerable to the adverse drought conditions of the country where the

[8] Temperature anomalies are defined as the difference between the temperature in a particular month and a long-term average temperature for that particular month. The usual value used to compute the average is of 30 years (Kumar et al., 2019). They are more important than actual temperature, given the difficulties in gathering data from some weather stations worldwide.

company headquarters are located, as these firms would be less likely to geographically diversify their earnings than highly capitalised firms.[9]

Finally, taking a starkly different approach, Nagar and Schoenfeld (2021) constructed a text mining index by counting the number of times the term 'weather' appeared in 10-K company reports of U.S. firms. They refined this index by means of part-of-speech tagging techniques. Nagar and Schoenfeld (2021) explained that their index should capture the multi-hazard exposure in Eq. (1) that a company may experience with different types of physical risks. To the extent that managers are aware of the impacts of weather-related events, Nagar and Schoenfeld (2021) argued that quantitative insights about firm exposure may be extracted by this kind of company (qualitative) information.

On the transition risk side, the studies in Table 1 generally construct the transition risk proxies using more homogeneous data sources and methodologies than the ones used to build physical risk measures. Görgen et al. (2020) constructed a score able to proxy for the several transition risk drivers in Eq. (2). In particular, they developed a 'Brown-Green-Score' (BG) which is defined as

$$\mathrm{BGS}_{i,t} = 0.70\ \text{Value Chain}_{i,t} + 0.15\ \text{Adaptability}_{i,t} + 0.15\ \text{Public Perception}_{i,t} \tag{7}$$

The variables Value $\text{Chain}_{i,t}$, $\text{Adaptability}_{i,t}$ and Public $\text{Perception}_{i,t}$ in Eq. (7) proxies for the terms *policy risk*, *technology risk* and *preference change* in Eq. (2), respectively.[10] To build the measure, Görgen et al. (2020) relied on 10 different ESG variables, retrieved from four different data providers. Görgen et al. (2020) argued that merging the ESG variables between these datasets should minimise the potential self-reporting bias, an issue that is particularly prominent across ESG providers (Avramov et al., 2021; Berg et al., 2019).

Other studies in Table 1 tend to focus on only one of the three firm-level emission variables described in Section 2, and researchers often argue that these variables should proxy for the three transition risk drivers in Eq. (2). Hsu et al. (2020) constructed a measure of emission intensity at the firm level by aggregating plant-level data from the Toxic Release Inventory (TRI) database in United States. The Trucost and Thomson Reuteurs' Asset4 ESG databases provide emission data at the aggregated firm level, both for the United States (Ardia et al., 2021; Bolton & Kacperczyk, 2021a; Cheema-Fox et al., 2021; In et al., 2017), and the entire world (Bolton & Kacperczyk, 2020). Moreover, these databases also provide data related to the three different types of scope emissions described in Section 2. Bolton and Kacperczyk (2020, 2021a) decomposed the three measures of carbon risk for each type of scope emission. Notably, as Busch et al. (2018) observed, there is very little variation in the reported scope 1 and 2 two emissions among data providers. This homogeneity in data and methods to build the transition risk proxies should be considered when analysing the differences in empirical results discussed in Section 3.1.3.

In conclusion, the remaining of studies in Table 1 analysed how both physical and transition risks were priced in the cross-section of stock returns. Engle et al. (2020) and Pástor et al. (2021) proxies this overall climate risk exposure by means of the E-scores provided by the MSCI and Sustainalytics databases, arguing that they should capture the different dynamics described in Eqs. (1) and (2). Engle et al. (2020) constructed E-score measures at the firm level by taking the difference between positive and negative E-scores subcategories. On the other hand, Pástor et al. (2021) built on the methodology described by Pástor et al. (2020). Furthermore, Gostlow (2019) distinguished between physical and transition risk exposure using asset level data provided by the Four Twenty-Seven (FTS) database. The computation of the climate risk measures provided by this database follows a structure similar to the one presented in Eq. (7).[11]

### 3.1.2. Economic rationale underlying the climate risk factors

The true challenge in climate finance studies analysing equity market is to identify the economic rationale that links portfolio returns to climate risk measures. As shown in Table 1, the wide spectrum of hypothesis used in this purpose indicated that there is still not a consensus about how the climate risk drivers described in Section 2 should affect the cross-section of stock returns. In this subsection, I give a detailed review of the assumptions underlying the climate risk factors.

If temperature risk represents a future risk to consumption, companies that are more exposed to long-term risks should provide higher risk premiums to investors today. This is the idea on which the theoretical model by Bansal et al. (2016) is grounded. Bansal et al. (2019) identified these companies as those in the higher decile of portfolios sorted on the book-to-market ratio (Hansen et al., 2008). Building on this idea, Bansal et al. (2019) found that value portfolios with higher dividend betas (i.e. those more exposed to macroeconomic growth risks) dictate monotonic and negative relationships with their temperature betas. Nagar and Schoenfeld (2021) took a simpler approach, showing that their text mining indices can track firm-specific impacts to natural disasters. Specifically, by applying an event study methodology, Nagar and Schoenfeld (2021) showed that firms with the highest text mining index values suffered the worst equity market responses after several hurricane events in the United States.

The economic rationale underlying the transition risk factors can be more thoroughly explained. The portfolio built by Görgen et al. (2020) aimed to mimic the three underlying risk factors in Eq. (2) in returns. Similar argumentations can be made for the climate risk measures used by Gostlow (2019). For the remaining of studies in Table 1, one must understand how the emission variables are related to the cross-section of stock returns. As Bolton and Kacperczyk (2021a) argued, the total amount of emissions should proxy for the long-term company's exposure to transition risks, as it is likely that regulations aimed to curb emissions are targeted more toward these types of firms. The opposite is true for the year-by-year changes in emissions, as this measure should capture the short-term effects of transition risks on stock returns. The economic rationale behind the emission intensity measure is explained using two different channels. Hsu et al. (2020) assumed this measure should proxy for the climate policy risk exposure of pollutant firms, so it is allowed to play a similar role as the total amount of firm emissions as in Bolton and Kacperczyk (2021a). In the works of Bolton and Kacperczyk (2020, 2021a), emission intensity should be related to the exclusionary screening process applied by institutional investors. In this case, the aim is to test the divestment hypothesis (Hong & Kacperczyk, 2009). This hypothesis would hold if the carbon intensity measure were (i) positively related to stock returns and (ii) negatively related to the holdings of institutional investors. The latter point would be observed in the cross-section if carbon-intensive stocks were deemed to be 'sin' stocks by institutional investors (i.e. companies involved in producing alcohol, gaming and tobacco, as explained in Hong and Kacperczyk (2009)). The resultant carbon premium would be then explained by the under-diversification opportunities provided by carbon stocks.

Another strand of studies in Table 1 used the economic tracking portfolio methodology to relate portfolio returns to the climate risk measures.[12] If equity prices change according to the arrival of climate change information, one could construct a portfolio of assets that can track news about climate risks. In this way, news can be either (i) a shock in the annual level of temperature (Balvers et al., 2017); or (ii) a text mining index designed to proxy for the arrival of climate

[9] The same argumentation also holds when temperature anomalies or other kinds of hazard are analysed at the firm level.

[10] Görgen et al. (2020) explained that the value of the deterministic weights in Eq. (7) are the results of several workshops held with academics and practitioners.

[11] For more information, see at: https://427mt.com/.

[12] In the asset pricing literature, such a methodology is also often referred to as the 'mimicking portfolio approach'.

change information in financial markets (Ardia et al., 2021; Engle et al., 2020). Economic tracking portfolios can be used to construct either risk factors or hedging portfolios (Lamont, 2001). Balvers et al. (2017) used size and value portfolios as basis assets to construct a temperate risk factor, as these portfolios should have higher levels of vulnerability to temperature shocks. Engle et al. (2020) exploited firms' E-scores to build a hedging portfolio against climate risks. The underlying hypothesis in the work of Engle et al. (2020) is that if green stocks would rise in value when climate information hit financial markets, these stocks would represent a simple asset to dynamically hedge against climate risks.

Pástor et al. (2020) formalised the idea applied by Engle et al. (2020) in a theoretical equilibrium model, where assets are priced by both a market and an ESG (or green) factor. The economic rationale in the Pástor et al. (2020) model is that while green assets have lower *expected* returns because they provide a hedge against climate risks, they could outperform brown stocks if the variable *preference change* in Eq. (2) shifted unexpectedly. Thus, these unanticipated changes in the consumer and investor demands would then lay the ground for *unexpected* (and positive) returns due to (i) cash-flow news via the consumer channel; (ii) discount-rate news by means of the investor channel; or both (Campbell & Shiller, 1988; Campbell & Vuolteenaho, 2004). Ardia et al. (2021) and Pástor et al. (2021) empirically tested the theoretical predictions of the Pástor et al. (2020) model.

Although the economic rationale underlying the climate measures illustrated above is compelling, a climate risk premium would emerge if market participants correctly *understood* these risks (Andersson et al., 2016). The studies in Table 1 employ both a direct and an indirect approach to test market efficiency in pricing climate risks.

The papers analysing the pricing of physical risks began with an indirect assumption. In particular, these studies analysed whether the realisations of physical risk measures in specific countries are informative regarding the profitability of companies that operate in those countries (Ding et al., 2020; Hong et al., 2019). These tests were implemented using either portfolio sorting (Hong et al., 2019) or cross-sectional sorting running Fama and MacBeth (1973) regressions (Kumar et al., 2019). Again using Eq. (6) as an example, the portfolios were sorted according to the estimated value of $b_i$ up to a certain year $t$. Given that lower values of $b_i$ are associated with higher values of drought (when the PDSI index is used), one would expect that the future profitability of firms in the resultant portfolios to be lower (Hong et al., 2019). These tests were applied both in specific industries, as agriculture and related sectors (Ding et al., 2020; Hong et al., 2019; Jiang & Weng, 2019) or across the whole economy (Kumar et al., 2019). The majority of studies in Table 1 found that firms' profits can be predicted for time horizons quite long, spanning from one (Ding et al., 2020; Kumar et al., 2019), up to three years (Hong et al., 2019). However, in an efficient market, such a pattern should not forecast stock returns as well, as these portfolio rankings are publicly available. In other words, stock prices should already embed this kind of information (Hong et al., 2019). Unlike the studies analysing physical risks, the works in Table 1 assumed that transition risks were underpriced (Cheema-Fox et al., 2021; In et al., 2017) before applying formal asset pricing tests. Given that the methodologies employed to construct risk-adjusted trading strategies are similar for both physical and transition risks, I review both methods in Section 3.1.3.

### 3.1.3. Climate change risks in the cross-section of stock returns

In this final subsection, I explore the mixed evidence about climate risk pricing in the equity market. First, I discuss the implications of studies that found that climate risks are priced. Next, I review the actual debates about the parameters $\alpha_p$ and $\sigma^2_{\varepsilon,p}$ in Eqs. (4) and (5), respectively.

On the physical risk side, only Bansal et al. (2019), Balvers et al. (2017) and Nagar and Schoenfeld (2021) found that physical risks represent an extra source of market risk priced in financial markets. The conclusions of these studies are important not only for asset pricing but also for policy implications. Specifically, the true aim in Bansal et al. (2019) was to provide a semi-parametric estimate of the social cost of carbon. If the equity market prices temperature risks, then such information is embedded in the estimated temperature elasticity of equity valuations. Using the total global emissions in 2017 as input, they estimated a social cost of carbon of nearly 0.4% of world Gross Domestic Product (GDP). Balvers et al. (2017) found that adding their temperature factor to the Fama and French (1993) factors in Eq. (4) allows to capture a higher amount of cross-sectional variation in industry-sorted portfolios. Balvers et al. (2017) framed their findings in light of the one-to-one relationship between the cost of capital and GDP per capita growth, as found in Henry (2003). Thus, the result that the cost of equity capital attributed to uncertainty about temperature changes is 0.22% should be viewed in a more broad sense as a (present) value loss of 7.92% of wealth for the US economy. Additionally, Nagar and Schoenfeld (2021) found that the parameter $\alpha_p$ in Eq. (4) of weather-beta sorted portfolios becomes insignificant once they control for their weather risk factor. In other words, the weather premium proxies for a new type of systematic risk capable of improving the prediction of the cross-section of stock returns in the US. Notably, their results overcame the hurdles set by Harvey et al. (2016), thus mitigating possible data snooping concerns.

Some studies in Table 1 found the evidence of a carbon premium in the cross-section. However, it remains unclear which transition risk measure can better explain the carbon premium. Bolton and Kacperczyk (2021a) found that portfolios sorted on the total level and the year-by-year change in emissions were valued at discount. These facts are true regardless of the type of scope emission analysed. Bolton and Kacperczyk (2021a) further showed that the carbon premium is not linked to the emission intensity measure. The findings of Bolton and Kacperczyk (2021a) were echoed by Bolton and Kacperczyk (2020) at the international level, although not all countries are pricing carbon risk to the same extent. Importantly, for both Bolton and Kacperczyk (2020, 2021a), the existence of a carbon premium cannot be explained by the divestment hypothesis. Bolton and Kacperczyk (2020, 2021a) found that institutional holdings seem to be negatively related to the emission intensity measure for some industries, but, again, stock returns are not related to this quantity. On the other hand, Hsu et al. (2020) discovered that the carbon premium is related to the emission intensity measure. However, as revealed by Bolton and Kacperczyk (2020), several robustness tests allowed Hsu et al. (2020) to confute the divestment hypothesis. Hsu et al. (2020) explained the observed premium providing a general equilibrium model and they showed in their model that investors learn from the *signal* of a possible regime change in climate mitigation policies. The different stocks' exposures to such a regime change may explain why investors require a pollution premium in the cross-section of stock returns.

Nevertheless, these findings were not corroborated by the remaining studies in Table 1. The tests of market efficiency were implemented using either portfolio sorting (Cheema-Fox et al., 2021; In et al., 2017; Kumar et al., 2019), or cross-sectional sorting (Hong et al., 2019). In the former case, the investment strategy can involve either a trading strategy in the spirit of Jegadeesh and Titman (1993), or the construction of zero-cost portfolios (Kumar et al., 2019). The 'winner' portfolios, when either the physical or the transition risks are analysed, are considered the ones with the lowest sensitivity to the climate risk measure, whereas the opposite is true for the 'loser' portfolios. Regardless of the approach used, however, the portfolios ranked on climate risk sensitivities seem to provide profitable, *risk-adjusted* trading strategies. While not always large in magnitude (Cheema-Fox et al., 2021; Hong et al., 2019), or fading over a short period of time (Kumar et al., 2019), the arbitrage opportunities found in In et al. (2017) and Jiang and Weng (2019) stretched over 10 and 20 years, respectively, indicating that the stock market may effectively underreact to climate risks. The conclusion by In et al. (2017) and Jiang and Weng (2019) was that climate change represents an extra source of market risk that may not be proxied by traditional factors commonly used in the asset pricing literature, such as market, size, value and momentum.

The empirical findings in Ardia et al. (2021) and Pástor et al. (2021) provided another interpretation for the observed mispricing in studies testing market efficiency, particularly on the transition risk side. Also Ardia et al. (2021) and Pástor et al. (2021) found that a portfolio that is long green stocks and short brown firms exhibits a positive alpha, controlling for other known risk factors in the asset pricing literature. Ardia et al. (2021) and Pástor et al. (2021) showed that such an outperformance is related to both the *preference change* channels in Eq. (2), and thus to both positive cash-flow and negative discount rate news for green stocks. To further show that such an outperformance is due to unexpected revaluations during the estimation period, Pástor et al. (2021) constructed a counter-factual green factor assuming zero shocks to climate concerns. The striking result in Pástor et al. (2021) was that, in absence of climate news, the green factor performance would be essentially *flat*. Additionally, the findings by Ardia et al. (2021) and Pástor et al. (2021) are coherent with some of the results observed in other studies in Table 1. First, Görgen et al. (2020) found that the nonexistence of a carbon premium is related to an unpriced cash flow change for both brown and green stocks, rather than to the parameter $\sigma^2_{\epsilon,p}$ in Eq. (5). Second, their results were also coherent with the positive out-of-sample performance of the hedging portfolio in Engle et al. (2020), given that their portfolio is constructed to have *unexpected* returns with maximum correlation to climate change news.

Overall, the contrasting evidence among the studies in Table 1 echoes the known issue of the joint tests of the efficient market hypothesis and the risk adjustment procedure (Fama, 1970, 1991). To provide further insights about the mixed evidence described thus far, Table 2 shows the number of traditional risk factors employed by each study when testing the climate-sorted portfolios using Eq. (4).

If the hypothesis advanced by In et al. (2017) and Jiang and Weng (2019) were true, one would expect the priced climate risk factors identified in the studies in Table 2 to be orthogonal to other known risk factors in the asset pricing literature. Bansal et al. (2019) did not control for firm-level risk factors but only for consumption growth, arguing that temperature fluctuations should be exogenous to firm-level characteristics. Balvers et al. (2017) regressed the size and value premiums on their temperature risk factor and found that some of the explanatory power of the Fama and French (1993) factors may be related to stocks' exposure to the temperature risks. On the one hand, one could then argue that studies in Table 2 testing market efficiency in pricing physical risks that control for these factors should be coherent with the investor irrationality hypothesis. On the other hand, Nagar and Schoenfeld (2021) found that there is a great heterogeneity in the market capitalisation across their weather-sorted portfolios, meaning that physical risk is not a size effect. Thus, the risk premium found by Nagar and Schoenfeld (2021) pointed toward an incorrect risk-adjustment procedure for studies in Table 2 analysing physical risk pricing. Similar arguments can be made about the pricing of transition risks (In et al., 2017). However, given that studies analysing green stocks' outperformance tend to construct trading portfolios using similar data and samples when applying asset pricing tests (Ardia et al., 2021; In et al., 2017), it is important to keep in mind that '*high realized returns do not always indicate high expected returns, especially if they are realized over a relatively short period*' (Pástor et al., 2021). Finally, as shown in Table 2, the transition risk factors, unlike the physical risk factors, may carry greater quantities of independent information. Although the identified carbon premium is not always orthogonal to other known systematic factors (Hsu et al., 2020), Bolton and Kacperczyk (2021a) found that this premium is robust to the possibility that cash flow news could drive results, meaning that some of the transition risk channels in Eq. (2) may effectively be priced correctly in the equity market.

To summarise, the empirical evidence presented in this section leaves one with a certain degree of uncertainty in understanding how climate change risks are shaping the form of Eq. (4), and, in turn, the theoretical predictions of macro-financial models. In particular, is the stock market really inefficient in pricing climate change risks? Are the risk adjustment procedures used in Table 2 incorrect? And, if the answer to the last question is positive, do the risk factors identified in Table 2 have a risk-based or a behavioural explanation? In Sections 4.1 and 4.2, I address these issues, linking top-down evidence in light of empirical findings resulting from the analyses of bottom-up approaches.

## 4. Bottom-up approaches: Focus on firms' and investors' characteristics

Bottom-up approaches represent another way the climate finance literature has been used to model the impact of climate change risks in the equity market. The literature in this direction has been ampler, and studies can be divided into the following groups: (i) micro-econometric approaches; (ii) event studies and (iii) surveys. The combined evidence resultant from bottom-up studies is of utmost importance for top-down approaches analysing the equity market. Such evidence could shed light on how the climate risk channels, described in Section 2, could determine the cross-sectional variation in stock returns described in the previous section.

The methodology used by **micro-econometric approaches** can be summarised using the following framework. Let $z_{i,j,t}$ be a variable related to a firm $i$, operating in the industry $j$, during the fiscal period $t$. The suffix $i$ can refer to either one of the firm's establishments in the sample (Addoum et al., 2021) or the whole company (Anton, 2021). The suffix $t$ can relate to either fiscal years (Huynh & Xia, 2021), quarters (Addoum et al., 2021), or months (Huynh & Xia, 2021). The variable $z_{i,j,t}$ can represent (i) a measure of operating performance, such as sales growth (Addoum et al., 2020) or return on assets (ROA, Trinks et al. (2020)); (ii) one of the three emission variables discussed in Section 2; (iii) a measure of firm's innovation, such as R&D expenses or the number of patents filed by the firm $i$ (Chu et al., 2020); (iv) stock returns, when using a cross-sectional regression (Huynh & Xia, 2021); or (v) a measure of earning forecast surprises (Pankratz et al., 2019). Studies in climate finance model the impact of climate risks on $z_{i,j,t}$ via the following regression:

$$z_{i,j,t} = \theta + \phi \text{ Climate Risk}_{i,t-k} + X_{i,t-k} + \epsilon_{i,j,t} \tag{8}$$

where $\theta$ is a vector meant to capture several types of fixed and time effects at the firm level. The term $X_{i,t-k}$ in Eq. (8) is a vector of firm-specific control variables, such as market-to-book ratio, firm size and book leverage. Moreover, the subscript $k$ in Climate $\text{Risk}_{i,t-k}$ can be equal to zero according to the specific analysis applied (Bartram et al., 2021). The error term $\epsilon_{i,j,t}$ is usually clustered at both the firm and year (or other time frequencies) levels (Bolton & Kacperczyk, 2021b), but it can also account for *spatial* correlation across errors (Addoum et al., 2020). In climate finance studies analysing physical and transition impacts, the interest in Eq. (8) is related to the coefficient $\phi$ of the variable Climate $\text{Risk}_{i,t-k}$. In Sections 4.1 and 4.2, I explain how such a variable may be related to firm-level variables, along with the asset pricing implications of these findings.

The high data requirements dictated by micro-econometric approaches pushes researchers to utilise more manageable methodologies to see how the financial market reacts to climate-related events. **Event studies** allow to quantify the importance investors attach to the arrival of climate change information. The empirical evidence found in these studies is important for three reasons. First, both types of equilibrium models introduced in Section 3 predict that assets more prone to climate change risks should decrease in value when a climate-related shock occurs (Giglio et al., 2020). Second, event studies reveal the degree to which the equity market anticipated at least part of the climate-related information, in particular on the physical risk side. Griffin et al. (2019) explain well this point:

**Table 2**
Climate risks and traditional risk factors.

| Study | MKTRF | SMB | HML | MOM | LIQ | RMW | CMA | IDIO | Is climate risk priced? |
|---|---|---|---|---|---|---|---|---|---|
| Balvers et al. (2017) | ✓ | ✓ | ✓ | | | | | | |
| Bansal et al. (2019) | ✓ | | | | | | | | |
| Bolton and Kacperczyk (2021a) | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| Bolton and Kacperczyk (2020) | ✓ | ✓ | ✓ | ✓ | | | | ✓ | Yes |
| Engle et al. (2020) | ✓ | ✓ | ✓ | | | | | | |
| Hsu et al. (2020) | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| Nagar and Schoenfeld (2021) | ✓ | ✓ | ✓ | | | ✓ | ✓ | | |
| Ardia et al. (2021) | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| Cheema-Fox et al. (2021) | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| Ding et al. (2020) | ✓ | ✓ | ✓ | ✓ | | | | | |
| Görgen et al. (2020) | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| Gostlow (2019) | ✓ | ✓ | ✓ | ✓ | | | | | |
| Hong et al. (2019) | ✓ | ✓ | ✓ | ✓ | | | | | No |
| In et al. (2017) | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | |
| Jiang and Weng (2019) | ✓ | ✓ | ✓ | ✓ | | | | | |
| Kumar et al. (2019) | ✓ | ✓ | ✓ | ✓ | | | | | |
| Pástor et al. (2021) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |

*Notes*: The table shows the number of traditional systematic factors that have been used from studies in Table 1 to adjust for risk exposure when testing Eq. (4). The columns are related to the excess return on the (i) market factor (MKTRF); (ii) size factor (SMB, Fama and French (1993)); (iii) value factor (HML, Fama and French (1993)); (iv) momentum factor (MOM, Carhart (1997)); (v) liquidity factor (LIQ, Pástor and Stambaugh (2003)); (vi) profitability factor (RMW, Fama and French (2015)); (vii) investment factor (CMA, Fama and French (2015)); and (viii) idiosyncratic risk factor (IDIO, Goyal and Santa-Clara (2003)), respectively.

> '*If investors already price accurately the full range of future weather contingencies (including rare outcomes) in their return expectations conditional on the evidence from extreme weather and climate science, and if they already know that firms are well-adapted to heat [or other] extremes, then one should not expect a biased investor reaction positive or negative to an extreme high surface temperature (EHST) event. Alternatively, (...) should an EHST event correct for an underpricing of physical climate risk, then the new market equilibrium will likely induce a significant and permanent reduction in equity price*'.

Third, and related to the second point, a fundamental issue in event studies is the choice of the factor model to compute benchmark returns. Thus, to provide more evidence regarding the discussion in Section 3, I reviewed only studies that took firm characteristics into account when describing abnormal returns around climate-related events.

Finally, **surveys** are another useful tool to answer possible questions that could not be easily addressed by means of tabular (i.e. quantitative) data (CFA, 2020). The surveys presented in this review were conducted on (i) investors (Krueger et al., 2020); (ii) firms (Amel-Zadeh, 2021); and (iii) consumers (Ricci & Banterle, 2020).

Albeit different in nature, the main discriminants behind the observed results provided by bottom-up approaches can be summarised as follows: (i) differences in firm level impacts and (ii) differences in investors behaviour. These two features allow to address directly the anomalies identified in Section 3.1, and, in particular, the joint tests of risk adjustment technique and efficient market hypothesis. Specifically, the possibility of new firm-level measures to keep into account in constructing factor models or investor behavioural biases toward climate change risks is analysed in 4.1 and 4.2, respectively.

### 4.1. Firm level impacts of climate change risks

One important point from the discussion in Section 3 is that one must understand how firm-level characteristics are related to the climate risk drivers described in Section 2. Empirical answers to this issue are crucial for several reasons. First, understanding the economic and financial channels driving firm exposure to climate shocks could foster the construction of a measure aimed to build tradable risk factors. If climate-exposed stocks are subject to common shocks, there will be a common variation in the returns of companies with similar levels of this climate risk measure. Second, whether these risk factors should represent a new type of systematic risk strictly depends on empirical evidence regarding the systematic impacts of climate shocks on firms. Third, it is also important to investigate whether the risk factors widely used in asset pricing literature may *proxy* for these exposures (such as value and size premium, as found in Balvers et al. (2017)). The last point still represents an interesting open question, as will be discussed in this and the next section.

Given the different types of datasets and methodologies reviewed in this review, I described how studies in climate finance used to model physical and transition impacts at the firm level in Sections 4.1.1 and 4.1.2, respectively. Additionally, I describe the possible inferential issues in using one econometric specification over another, particularly on the physical risk side. Finally, I discuss whether the documented impacts should be deemed systematic or not and the implications of these findings at the top-down level. Table 3 summarises the results of studies on climate finance analysing climate risks at the firm level.

#### 4.1.1. The effects of climate and natural hazards on listed firms

When modelling physical risks, the variable Climate $\text{Risk}_{i,t-k}$ in Eq. (8) can assume different forms depending on the specific *hazard* in Eq. (1) the researcher is analysing. If she wants to model temperature and precipitation risks on $z_{i,j,t}$, then Climate $\text{Risk}_{i,t-k}$ can be either (i) the level of temperature or precipitation averaged over a certain period of time (Anton, 2021) or (ii) the number of days during the month that the levels of temperature or precipitation exceed or fall below certain thresholds (Pankratz et al., 2019). The term Climate $\text{Risk}_{i,t-k}$ is also allowed to take more complex forms if temperature risk is modelled, allowing for non-linear impacts on $z_{i,j,t}$ (Addoum et al., 2021). If a natural disaster is analysed, then Climate $\text{Risk}_{i,t-k}$ is usually a dummy variable taking the value of one if a certain hazard hit the city (Pankratz et al., 2019) or the county (Huynh & Xia, 2021) where the establishments of firms are located. When analysing physical risks at the firm level, Eq. (8) can estimated using either (i) a panel regression (Addoum et al., 2020; Huynh & Xia, 2021); (ii) a quantile regression (Anton, 2021); (iii) a spatial econometric (Lucas & Mendes-Da-Silva, 2018); or (iv) a difference-in-difference (DID) estimation framework (Alok et al., 2020).

**Table 3**
Bottom-up approaches: Firm-level evidence.

| Study | Climate risk | Countries | Sectors | Main results | Main asset pricing implications |
|---|---|---|---|---|---|
| Addoum et al. (2020) | Extreme temperatures | USA | Multiple | Little operating effects on firms | Temperature risk should not be priced |
| Addoum et al. (2021) | Extreme temperatures | USA | Multiple | Positive and negative operating effects across sectors | Temperature risk should be priced |
| Akey and Appel (2021) | Policy risk | USA | Multiple | Corporate parents reallocate their emissions via subsidiaries | Lower market expectations about carbon risk |
| Bartram et al. (2021) | Policy risk | USA | Multiple | Constrained firms reallocate their emissions in other states | Lower market expectations about carbon risk |
| Bolton and Kacperczyk (2021b) | Technology risk | 66 countries | Multiple | Green firms reduce emissions more than brown firms | Possible unexpected and positive revaluations for green stocks |
| Dai et al. (2021) | Preference change | USA | Multiple | Costumers hinder the reallocations of emission of their suppliers | Higher market expectations about carbon risk |
| De Haas et al. (2021) | Technology risk | 22 countries | Multiple | Constrained firms do not adopt low-carbon investment strategies | Constrained firms may be more exposed to long-term technology risks |
| Huynh and Xia (2021) | Natural disasters | USA | Multiple | Negative operating impacts across firm establishments | Natural disaster risks should be priced |
| Lv and Bai (2021) | Technology risk | China | Energy | Increase in the amount of R&D after the introduction of a mitigation policy | Possible unexpected ad positive revaluations for brown stocks |
| Pankratz et al. (2019) | Extreme temperatures | 57 countries | Multiple | Negative operating effects for SMEs | Temperature risk should be priced |
| Pankratz and Schiller (2021) | Extreme temperature and floods | 71 countries | Multiple | Negative operating effects on supplier and corporate costumers | Physical risks may be a systematic risk |
| Rao et al. (2021) | Extreme precipitation | India | Multiple | Long-lasting operating effects on impacted firms | Precipitation risk should be priced |
| Trinks et al. (2020) | Technology risk | 47 countries | Multiple | Carbon-efficient firms have higher operating performances | Possible unexpected and positive revaluations for green stocks |
| Xu and Kim (2021) | Policy risk | USA | Multiple | Constrained firms reallocate their emissions in other states | Lower market expectations about carbon risk |

As discussed in Section 2, modelling the impacts of climate and natural disasters at the firm level requires different types of datasets. In general, micro-econometric approaches analysing temperature and precipitation risks tend to prefer reanalysis datasets because they provide greater spatial–temporal coverage than observational datasets.[13] If the analysis is conducted in the United States, the PRISM dataset is generally used (Addoum et al., 2020, 2021). On the other hand, the European Centre for Medium-Range Weather Forecast's ERA5 dataset has been employed in international settings (Pankratz et al., 2019; Pankratz & Schiller, 2021). With respect to natural disaster datasets, both the Emergency Events Database (Pankratz & Schiller, 2021), and the Spatial Hazard Events and Losses Databases of the United States (Alok et al., 2020; Huynh & Xia, 2021) have been used to gather data about disaster losses at the national or regional levels, respectively. To account for firms' locations in the United States, the National Establishment Time-Series (NETS) provides sales and other kinds of metadata (e.g., addresses) for each U.S. establishment owned by each public firm (Addoum et al., 2020). At the international level, the Orbis database can be used to retrieve data regarding sales and addresses of firm headquarters and their establishments (Pankratz & Schiller, 2021). However, in Orbis the financial accounting variables are not always available for firm branches. Thus, Pankratz and Schiller (2021) limited their analysis to only SMEs, assuming these firms to be less geographically diversified (as in Hong et al. (2019)). Notably, any of the studies in Table 3 made use of innovation data to construct $z_{i,j,t}$ in Eq. (8). Studies in climate finance analysing physical impacts at the firm level infer the firm's adaptation capacity through analysing specific variables of the income statements. Thus, if a certain accounting variable in the bottom line of the income statements (e.g., firm's earnings) is negatively affected by physical risks, then it is likely that these effects are net of firm's hedging activities (Addoum et al., 2021).

Once Eq. (8) is estimated at the firm or establishment level, studies in climate finance analysing physical risks at the firm level generally proceed as follows. First, these studies analyse the statistical significance of the coefficient $\phi$ in Eq. (8). Second, they may (Addoum et al., 2021; Huynh & Xia, 2021), or may not (Anton, 2021) analyse how market participants react to these impacts. In this subsection, I review the first set of results, and I analyse equity market responses in Section 4.2.[14]

Some studies in environmental economics have concluded that the negative effects of climate hazards mainly affect developing economies (Dell et al., 2012; Hsiang, 2010). These works have focused on the impacts on macroeconomic aggregates such as GDP, and it is only recently that researchers in corporate finance have begun to explore the implications of climate hazards at the firm level. For instance, Rao et al. (2021) analysed the impact of the monsoon season on the Indian firms' investment processes. They found that firms more exposed to extreme rainfall conditions increased their levels of capital expenditures and that such a pattern tends to persist for up to three years after extreme precipitation. Nevertheless, climate hazards may have *both* positive and negative impact on firm level outcomes. Lucas and Mendes-Da-Silva (2018) documented extreme temperatures, and rainfall positively impacted the performance of Brazilian energy firms, consistent with the increase in energy consumption during these months.

Merging the PRISM and NETS databases, Addoum et al. (2020) found that, on average, neither sales nor productivity growth rates were impacted by extreme temperature levels among the populations of establishments and firms in United States. Addoum et al. (2020) concluded that their results were driven by the fact that the American listed firms have greater resources to adapt to extreme weather conditions than companies in developing countries. However, different

[13] Reanalysis datasets allow one to capture the spatial–temporal value of a certain meteorological variable within a certain grid. However, given that the meteorological variables are estimated across grids, one must remember that the resultant measurement error will depend on the data assimilation system used to construct the reanalysis dataset (Tankov & Tantet, 2019).

[14] This also explains why some studies analysing physical risks at the bottom-up level can be found both in Tables 3 and 4.

econometric settings when estimating Eq. (8) may have starkly effects on final inferences. In a subsequent paper, Addoum et al. (2021) found that when $z_{i,j,t}$ was aggregated at the industry-by-season level, quarterly earnings could be predicted in over 40% of US sectors (using the Global Industry Classification Standard, or GIC, six-digit code). More important is the fact that this kind of relationship is not only (i) bi-directional (as shown by Lucas and Mendes-Da-Silva (2018)); (ii) spatial and (iii) seasonal dependent, but it is also *non*-linear, a pattern well-documented in the environmental economics literature (Tol, 2009). Addoum et al. (2021) analysed what could determine such a sensitivity to extreme temperature risks. They showed that the demand (rather than supply) channel implied lower revenues for the affected sectors, an outcome explained by the effects that extreme temperature may have on consumers' behaviour (Graff Zivin & Neidell, 2014). Similar outcomes emerged from a recent survey by Amel-Zadeh (2021), who found that firms are worried about the effects of physical risks on consumer demand.

The effects on firm sales found in Addoum et al. (2021) have been echoed in a series of similar works. For instance, Hugon and Law (2019) and Pankratz et al. (2019) showed that firms headquartered in areas with higher regional temperature variations exhibit decreases in earnings during extreme hot periods. Notably, Hugon and Law (2019) found that larger (in terms of market capitalisation) and more geographically diversified firms do not exhibit the same negative effects (affirming the results by Balvers et al. (2017)). However, the empirical evidence about the economic channels driving the temperature impacts on firms' sales differed across studies. Whereas Anton (2021) and Pankratz et al. (2019) corroborated the evidence about the demand channel revealed by Addoum et al. (2021), Hugon and Law (2019) found that the supply channel was driving their results, particularly via an increase in operating expenses. In a recent paper, Pankratz and Schiller (2021) also found support for the supply channel. Using an international sample, Pankratz and Schiller (2021) showed how the negative effects of extreme temperatures and floods on suppliers could cause negative operating performances of their corporate customers.

The econometric setting is also relevant when Eq. (8) is estimated analysing the impact of natural disasters at the firm level. For instance, Dessaint and Matray (2017) found a statistically insignificant difference between sales growth of firms headquartered in affected counties and that of nearby firms. However, when the locations of firms were identified by considering all the firms' establishments in other counties, Huynh and Xia (2021) found that multiple climate hazards had an impact on overall firms' growth sales.

Overall, the combined evidence of micro-econometric approaches analysing physical impacts at the firm level leads the following conclusions. First, physical risks should neither be thought to belong only to agricultural or related sectors (Addoum et al., 2021) nor be limited to only temperature risks (Huynh & Xia, 2021). Second, because physical risks may impact both the supply and demand channels in different parts of the world (Pankratz & Schiller, 2021), it is likely that several companies in several sectors are exposed to various degrees to physical risks. Taken together, these results would justify the emergence of a systematic physical risk premium in the cross-section of stock return. The text mining measure used by Nagar and Schoenfeld (2021), although not complex in nature, may proxy for these multi-hazard exposures. However, little can be said regarding firms' adaptations to these risks. Taking the Nagar and Schoenfeld (2021) measure as an example, two firms with the same value of the text mining index may have two different types of innovation strategies to adapt to physical risks. Thus, modelling such an adaptation channel at the firm level is a promising avenue for future studies on climate finance.

#### 4.1.2. Firms' responses to transition risks and consumers' behaviour

As with physical risks, the variable Climate $\text{Risk}_{i,t-k}$ in Eq. (8) depends on the specific transition risk driver the researcher is designed to model at the firm level. Thus, there are three different ways to model the transition risks described in Eq. (2) by means of Eq. (8). When modelling *policy risk*, Climate $\text{Risk}_{i,t-k}$ is referred to a specific climate mitigation policy, which may be a market (Bartram et al., 2021) or a non-market-based mechanism (Akey & Appel, 2021). When modelling *technology risk*, the variable Climate $\text{Risk}_{i,t-k}$ may again coincide with a specific climate mitigation policy, but also with (i) a measure of carbon efficiency (Trinks et al., 2020); or (ii) the fraction of shares of firm $i$ held by an institutional investor during a specific fiscal period (Azar et al., 2021), in order to see whether investor pressure trigger firm carbon management practices. The effects of the investor channel of firm level outcomes are analysed in Section 4.2.2. Finally, if the consumer channel is analysed at the firm level, then Climate $\text{Risk}_{i,t-k}$ can represent either (i) the percentage of green-motivated costumers toward firm $i$ (Dai et al., 2021) or (ii) quantitative results obtained from consumer surveys (Ricci & Banterle, 2020). On the policy and technology risk side, *quasi*-experimental studies are often employed by researchers to ascertain the causal effects that policy and external shocks have on $z_{i,j,t}$ in Eq. (8). Exploiting the fact that these shocks are local, studies in climate finance tend to infer the causal effects of Climate $\text{Risk}_{i,t-k}$ on $z_{i,j,t}$ via a DID (Akey & Appel, 2021) or a triple-DID (Bartram et al., 2021) estimation framework. Nevertheless, in specific analysis, panel regression can also be used when transition risks are modelled using micro-econometric approaches (Trinks et al., 2020; Xu & Kim, 2021).

Given the multiple forms the variables $z_{i,j,t}$ and Climate $\text{Risk}_{i,t-k}$ can take in Eq. (8) when transitional risks are analysed, several types of datasets may be used. Plant level emissions in the US can be gathered using the TRI (Xu & Kim, 2021) or the Facility Level Information on GHGs Tool (Bartram et al., 2021) datasets. With respect to firm innovation, Thomson Reuters DataStream provides R&D expenditures at the national and international level, respectively, whereas firm patents can be gathered by the National Bureau of Economic Research patent databases for the United States (Chu et al., 2020). When analysing climate mitigation policy shocks, the dataset for the variable Climate $\text{Risk}_{i,t-k}$ in Eq. (8) is generally constructed by the researcher (Akey & Appel, 2021). Investor holdings data are generally retrieved from the 13F Thomson Reuters or FactSet databases (Azar et al., 2021). Finally, data about the consumer channel can be retrieved directly from consumer surveys (Ricci & Banterle, 2020), or from Compustat, which provides the amount of consumer expenditures toward firm $i$ for the United States (Dai et al., 2021).

Studies analysing the effects of policy risk are mainly interested in exploring how firm-level emissions vary according to the environmental regulation employed in a specific state (Bartram et al., 2021), or country (Ben-David et al., 2018). If environmental policies prove effective, one would expect that firms in the treatment group (i.e. the ones located in the state or country where the policy was applied) to exhibit lower levels of emissions, operating performance or both. Nevertheless, the majority of studies in Table 3 revealed that the regulatory arbitrage of firms allowed them to systematically overcome the effects of the policy measure, both at the state (Akey & Appel, 2021; Bartram et al., 2021; Xu & Kim, 2021) and country levels (Ben-David et al., 2018). Notably, these aggressive corporate environmental policies seem to be linked to certain firm-level characteristics. In particular, financially constrained firms relocated their emissions in other locations after the introduction of the California cap-and-trade program in 2013 (Bartram et al., 2021) and where probability of having environmental liabilities is low (Xu & Kim, 2021). Moreover, in some cases there is no evidence that these policy measures have affected the profitability of constrained firms (Bartram et al., 2021). These results may explain why the survey by Amel-Zadeh (2021) found that at the international level, firms have been ranking climate policy risks as less important than physical risks.

On the technology risk side, the results of micro-econometric approaches in Table 3 corroborate some of the outcomes found in Section 3. As Görgen et al. (2020) argued, their transition risk factor is unpriced because green firms are becoming greener than brown firm faster. Görgen et al. (2020) further explained that their risk factor is unpriced because its unanticipated changes are related to unexpected revaluations when both brown and green stocks surprise the market by adopting low-carbon strategies. Bolton and Kacperczyk (2021b) analysed firm commitments to reduce their carbon emissions worldwide. They found that the reduction in emissions mainly arose from commitments from greener firms, meaning those with fewer emissions. Furthermore, Trinks et al. (2020) demonstrated that at the international level, firms with higher levels of carbon efficiency (i.e. those with higher values of the ratio of target-to-actual carbon emissions relative to their peers) tend to have higher ROA and higher market valuations.

Also brown firms are acting to some extent to reduce their carbon exposure. Chu et al. (2020) documented that firms decrease their toxic emissions when their headquarters are located near places where environmental spills have recently occurred. Chu et al. (2020) explained this outcome in light of firms aiming to adapt to possible future environmental liabilities. Lv and Bai (2021) analysed how Chinese firms had responded to the introduction of the China's Carbon Emission Trading Mechanism. They showed that firms generally increased their R&D expenditures and that the market rewarded these companies with higher valuations. However, firm financial frictions seem to be major barriers to corporate innovation policies. For instance, De Haas et al. (2021) showed that firms with higher financial constraints operating in emerging economies tended to avoid carbon reduction plans in recent years. Xu and Kim (2021) explained how financial constraints may affect corporate environmental policies as follows:

> '*The optimal environmental abatement expenditures presuppose that the marginal cost of abatement equals the marginal reduction in expected legal liabilities. (...) As financial constraints unveil and drive up the cost of financing, the marginal cost of environmental abatement increases correspondingly. Holding other factors constant, financial constraints reduce firms' abatement activities and consequently increase total toxic releases.*'

Finally, the direct impact of the consumer channel on firms' financial outcomes has received little attention in the climate finance literature. This is unexpected for two reasons. First, as shown in Eq. (7), public concerns are given the same weight as firms' adaptability to a low-carbon economy. Moreover, recent studies in asset pricing emphasise how the relevance of firms' consumer capital may be reflected in the cross-section of stock returns (Dai et al., 2020; Dou et al., 2021). The only notable exception can be found in the work by Dai et al. (2021) and Ricci and Banterle (2020). Dai et al. (2021) demonstrated that firms supplying their products to green corporate consumers are less prone to relocating their quantities of scope 3 emissions to other countries. Ricci and Banterle (2020) surveyed Italian retail consumers and found that they shifted their purchasing behaviours toward green products after the Paris Agreement, in line with the prediction of the Pástor et al. (2020) model.

The impacts of transition risks at the firm level lead the following conclusions. First, certain studies have documented how historically the regulatory arbitrage of firms may mitigate the effects of climate policy risks, obscuring the possibility that policy risk is priced in the equity market. However, equities prices represent forward-thinking expectations about the cash flows of a firm. Investors' expectations about the effects of policies aimed to curb emissions nationally and worldwide may still make available a transition premium in the equity market. Having said that, these studies provide compelling evidence of how non-coordinated regulatory solutions may systematically distort investors' beliefs, in turn lowering the demand of a carbon premium in some countries, as reported by Bolton and Kacperczyk (2020). Second, firm financial constraints seem to be a relevant financial channel hindering firms' capabilities to adapt to a low-carbon economy, both in developed (Bartram et al., 2021) and developing countries (De Haas et al., 2021). On the one hand, Hsu et al. (2020) found that the carbon premium cannot be explained by financial constraints of firms, thus reinforcing the policy risk channel in United States. On the other hand, financial constraints may represent a relevant financial friction driving firm exposure to low-carbon technology risks in the long run. Therefore, integrating these considerations when developing the equilibrium models introduced in Section 3 would be a valuable avenue for future studies in climate finance. Additionally, future research is needed to investigate the direct effects that consumers may have on the cash flows of carbon intensive firms, given the non-negligible role that this channel plays in some of the models introduced in Section 3 (Pástor et al., 2020; Pedersen et al., 2020).

### 4.2. Investors' beliefs about climate change risks: Sentimental or fundamental?

A critical issue arising in Section 3.1 referred to the concerns of possible stock market inefficiency in pricing climate change risks, a result in accordance with recent theoretical works (Thomä & Chenet, 2017). Nevertheless, these studies contrast empirical works showing that climate risks are priced in the cross-section of stock returns (Hsu et al., 2020; Nagar & Schoenfeld, 2021). Thus, to provide more quantitative insights about how the stock market interacts with climate risks, it is crucial to answer the following questions:

- *Do* investors price climate-related risks in the equity market on an ex-ante or ex-post basis?
- *How* do investors utilise climate-related information?
- *When* did investors begin to analyse these kinds of data?

This subsection reviews the findings of the climate finance literature with respect to each of these questions, combining all of the empirical evidence provided by bottom-up approaches. Moreover, the focus here is not only on investors' behaviour but also on the different types of investors, given the heterogeneous effects they may exert on firm-level outcomes (Azar et al., 2021). Table 4 summarises the findings for studies analysing how investors are interacting with climate change risks in the equity market.

#### 4.2.1. When do climate change risks enter in stock prices?

The evidence provided in Section 4.1 has shown that climate-related events should represent a concern for investors in financial markets. If investors would correctly identify firms' exposure to climate risks in their return expectations (i.e. on an ex-ante basis), expected returns would be a good proxy of realised returns. In particular, investors' hedging demand for climate risks would allow the researcher to estimate the resulting climate risk premium in the cross-section of stock returns.

One of the main sources of investors' return expectations may be related to the valuation of sell-side analysts disseminating company information (Huynh et al., 2020). However, most studies have found that analysts may not drive a fair assessment of climate risks at the firm level. This fact may be one of the reasons why investors tend not to correctly price their portfolios' exposure on an ex-ante basis, particularly on the physical risk side.[15] On the one hand, Addoum et al. (2021) documented that some sell-side analysts consider the effects of extreme temperature in their quarterly valuations in the United States. On the other hand, Pankratz et al. (2019) showed that the opposite is true in an international sample. In particular, Pankratz et al. (2019) found that an increase in earnings deteriorations by firms due to extreme temperatures was systematically followed by negative performance analysts' surprises. Moreover, a number of studies revealed that the implied cost of capital (i.e. a proxy for expected returns, whose value is strictly dependent on analysts' evaluation models, according to

[15] I describe other possible explanations in Section 4.2.3.

**Table 4**
Bottom-up approaches: Investor-level evidence.

| Study | Financial actors | Countries | Period | Main results | Main asset pricing implications |
|---|---|---|---|---|---|
| Akey and Appel (2019) | Hedge funds | USA | 1991–2015 | Hedge funds are engaging with firms to foster carbon management practices | Investors are pricing carbon risk at the firm level |
| Alok et al. (2020) | Fund managers | USA | 1995–2016 | Fund managers overreact to natural disasters | Price reversal for exposed stocks |
| Amel-Zadeh (2021) | Institutional | – | – | Climate risks are a recent phenomenon in the financial industry | Estimating the correct sign of the climate risk premium may be challenging |
| Atanasova and Schwartz (2019) | Whole market | USA | 1999–2018 | Oil stock prices are negatively related to their quantities of unproved reserves | Investors are pricing carbon risk at the firm level |
| Azar et al. (2021) | Mutual funds | USA | 2005–2018 | Mutual funds are engaging with firms to foster carbon management practices | Investors are pricing carbon risk at the firm level |
| CFA (2020) | Institutional | – | – | Lack of disclosure does not foster a correct pricing of climate risks | Possible underpricing of climate risks because of a lack of disclosure from firms |
| Choi et al. (2020) | Retail investors | 64 countries | 2001–2017 | Investors demand green stocks during extremely hot months | Negative climate beta for green stocks |
| Flammer et al. (2021) | Institutional | USA | 2010–2016 | Investors are engaging with firms to increase the amount of climate-related disclosure | Investors value climate risk disclosure positively |
| Griffin et al. (2019) | Whole market | USA | 2003–2017 | Excess returns are lower when accounting for the size and value premiums | Temperature risks may be related to a size or a value effect |
| Huynh and Xia (2021) | Whole market | USA | 1990–2015 | Investors overreact to natural disasters | Price reversal for exposed stocks |
| Ilhan et al. (2021a) | Institutional | – | – | Lack of disclosure does not foster a correct pricing of climate risks | Possible underpricing of climate risks because of a lack of disclosure from firms |
| Krueger et al. (2020) | Institutional | – | – | Climate risks are a recent phenomenon in the financial industry | Estimating the correct sign of the climate risk premium may be challenging |
| Pankratz et al. (2019) | Analysts | 57 countries | 1995–2017 | Earnings surprises due to unanticipated extreme temperatures exposure | Anticipating physical risks may be challenging for investors |
| Ramelli et al. (2021) | Whole market | USA | 2016–2020 | Investors demand green stocks during events of policy uncertainty | Negative climate beta for green stocks |

Pástor et al. (2008)) is correctly priced for physical (Huynh et al., 2020) and transition risks (Chava, 2014). Nevertheless, these works cannot explain the number of anomalies documented in Table 1. In particular, the implied cost of capital focuses only on the ex-ante level of discount rates rather than on dynamic changes therein (Pástor et al., 2021). Specifically, when the climate risk premium is estimated over short-estimation periods, expected returns may differ from realised returns if unexpected news affects the equity market. The way in which the market responds to unanticipated climate events (i.e. climate risks are priced ex-post) may affect substantially the performance of the climate risk factor.

To analyse ex-post market responses to climate-related information studies in climate finance used both micro-econometric approaches and event studies. Clearly, the interest in event studies analysing transition news differs from the interest in studies examining physical news. In the former case, studies in climate finance generally explore the equity responses at the industry level and whether green firms increase in value during specific realisations of transition risks. In the latter case, event studies focused more on whether certain firm characteristics may drive ex-ante investors' expectations toward firms' vulnerability to these risks (Griffin et al., 2019).

With respect to transition risks, the empirical results by event studies confirmed some of the results found in Ardia et al. (2021) and Pástor et al. (2021). In particular, Ramelli et al. (2021) documented that after the 2016 presidential election of Donald Trump, a staunch supporter of the U.S. carbon industry, firms with higher ESG scores increased in value. Given that analysts' forecasts for these firms had not risen (i.e. the cash flow news hypothesis would not hold), Ramelli et al. (2021) concluded that this result was in line with the fact that climate-friendly stocks would have provided a hedge against unexpected policy shocks in coming years (supporting the discount rate news hypothesis). In a related study, El Ouadghiri et al. (2021) documented that during periods of increased public attention to environmental issues, standard indices with a higher carbon exposure underperformed more sustainable ones. Moreover, Diaz-Rainey et al. (2021) found that the announced withdrawal of the U.S. from the Paris Agreement negatively affected the oil and gas sector in the United States. This effect was consistent with the fact that investors had been gradually expecting future environmental liabilities for these companies, regardless of the actual effectiveness of climate mitigation policies. Notably, the above studies tend to focus on the U.S. market only. It would be valuable to analyse whether the documented excess returns would be lower in magnitude if one controlled for the priced transition risk factors found in Bolton and Kacperczyk (2021a) and Hsu et al. (2020).

As discussed in Section 2, physical risks are multidimensional (Pescaroli & Alexander, 2018; Tankov & Tantet, 2019), and thus several event studies have focused their attention only on a subset of specific climate-related events. For instance, Bourdeau-Brien and Kryzanowski (2017) analysed the impact of different natural disasters on equity returns in the U.S. market. Their work introduced the idea that a large ex-post event window is needed to measure the equity market response, as it takes some time to provide reliable estimates of the economic damages of the particular climate hazard of interest. Bourdeau-Brien and Kryzanowski (2017) found that while no reaction appeared in the short term, the stock market reacted positively and negatively after two to three months, but only for a small number of natural disasters. Nevertheless, they showed that neither the industry classification nor the firm size could explain the sign of abnormal returns at any event period length. On the other hand, Griffin et al. (2019) found that excess returns around EHST days are lower in magnitude if one takes into account the size and value premium, arguing that these two factors *may* proxy for market expectations about climate-related risks (thus confirming again the results found by Balvers et al. (2017) discussed in Section 3.1). However, these concerns were directly addressed by Lanfear et al. (2019), who examined whether natural disaster, in particular, hurricanes, could explain part of the size and value anomalies. They documented that small firms and growth stocks have been affected significantly *after* the realisation of these extreme events, although the most important outcome is the deterioration in stocks' liquidity. A similar result was found by Rehse et al. (2019), who showed the uncertainty effects generated by Hurricane Sandy on the real estate investment trusts market in the US. This finding reinforces the outcomes from Lanfear et al. (2019), who noted that '*risk-based explanations may not be sufficient and some sentiment-related factor is likely to be an important component for understanding our findings*'.

Supporting the hypothesis proposed by Lanfear et al. (2019), the evidence about micro-econometric approaches can be summarised by explaining that the ex-post reactions to physical risks in the stock market have been documented to be both undue (overreaction) and belated (underreaction).[16] In particular, the literature revealed that such a response is somewhat dependent on the personal traits well-documented in the behavioural finance literature (Bassi et al., 2013); what emerges is that market responses to physical risks are driven by both salience and local biases.

Using international data, Choi et al. (2020) found that retail investors exposed to unusual and local high temperatures (i.e. a salient event that proxies but does *not* represent climate change) tend to buy low carbon stocks and, at the same time, sell high carbon stocks. Given that no evidence of price reversal is observed in the subsequent months, Choi et al. (2020) concluded that this pattern would be in line with a slow belief updating in climate change risks. Donadelli et al. (2020) analysed how the equity market responds to tornado activity in the US. They found that equity responses are (i) bi-directional; (ii) industry-specific; (iii) local (in the sense that investors penalised more firms with the headquarters near to the occurrence of these kinds of events) and (iv) lagged (as in Bourdeau-Brien and Kryzanowski (2017)). This sluggish market response in pricing physical risks would justify the presence, even if temporary, of risk-adjusted trading opportunities as identified by Hong et al. (2019) and Kumar et al. (2019).

As regards to overreaction, Alok et al. (2020) documented that fund managers tend to overreact to acute physical risks, as the affected firms sold by managers tend to outperform less exposed ones in the two years following a climate disaster. Huynh and Xia (2021) extended the results of Alok et al. (2020) to the entire population of U.S. investors, providing a possible behavioural explanation for the premium identified in Nagar and Schoenfeld (2021). In fact, Huynh and Xia (2021) found that the overreaction of investors could explain why firms more exposed to natural disasters may *outperform* less exposed ones. In particular, Huynh and Xia (2021) showed that investors' overreactions depressed current stock prices, causing future returns to be higher. The overreaction hypothesis was further confirmed given that Huynh and Xia (2021) found, as discussed in Section 4.1.1, that the fundamentals of affected firms deteriorated after the disasters. Notably, greener firms, although they suffered similar losses in sales after disasters, were the ones that suffered the lowest selling pressures.

There are several implications of observed results in this subsection for top-down approaches. First, these results suggest that the economic tracking portfolio proposed by Lamont (2001) may be useful for addressing the fact that the market tends to misprice physical risks. In fact, as Lamont (2001) explained:

> '*(...) suppose that asset markets are inefficient, irrational sentiment affects market prices, and returns are partially predictable. In this case, as long as asset prices reflect some information about future economic variables, tracking portfolio returns will still be useful for hedging and forecasting*'.

[16] The evidence of investors' behavioural biases toward climate change risks have been analysed only with respect to the realisations of physical impacts. The only exception can be found in the work of Benz et al. (2020), who showed how institutional investors tend to herd with respect to their decarbonisation strategies.

Moreover, it seems that green assets tend to empirically pay off in times of negative climate change realisations. Here, the phrase 'negative climate change realisations' is intended in a broad sense, as the studies presented above showed that investors demand green assets both after extreme weather events (Choi et al., 2020; Huynh & Xia, 2021), and uncertain policy shocks (Ramelli et al., 2021). Together, these results may not only explain the superior performance of green strategies found in Table 1 but also justify a negative climate beta toward climate risk factors for green stocks. These results were assumed in the theoretical model proposed by Pástor et al. (2020). I discuss the implications for expected returns of these patterns in Section 4.2.3.

#### 4.2.2. Investors' engagement and the value of climate risks disclosure

Once the way investors respond to these kinds of events is acknowledged, it is important to understand how they tend to process climate-related information. Investor surveys provide compelling evidence on this point. The Chartered Financial Analyst Istitute CFA (2020) found that 60% of portfolio managers do *not* incorporate climate risks in their analysis. The main barriers for investors are both the little knowledge of climate risk integration in the investment process (Bouchet et al., 2021) and a lack of disclosure from firms, which does not allow investors to develop proper measurement tools. The same results were also found by Amel-Zadeh (2021) and Krueger et al. (2020), thus indicating that investors are '*still learning how to deal with these risks*' (Krueger et al., 2020). In spite of these issues, investor surveys seem to indicate that in recent years investors have been actively *engaging* with firms to manage their portfolios' climate change exposure.

Consistent with Pástor et al. (2020), investor surveys have shown that there may be both financial and nonfinancial reasons why investors would like to decarbonise their portfolios. The main financial reason for institutional investors seems to be the protection of their reputations (Krueger et al., 2020), which in turn may attract investment clients particularly concerned with environmental aspects (Ceccarelli et al., 2019). This result reflected what studies at the bottom-up level found. Not only mutual funds (Azar et al., 2021), but also hedge funds (Akey & Appel, 2019; Chu & Zhao, 2019) have been cooperating with firms to develop corporate policies to lower the emissions of targeted companies. The final goal for investors is reducing the carbon footprints of their portfolios. These results align with those of Shive and Forster (2020), who found that firms tend to emit less when mutual fund ownership is higher. Moreover, although these sustainable campaigns require a significant amount of financial resources to influence the target firm (Dimson et al., 2020) and the rate of their successful completion is generally low, investor surveys have revealed that few investors divested if not satisfied with firms' responses (CFA, 2020; Krueger et al., 2020). In fact, divestment may have detrimental effects, particularly for large passive investors (Azar et al., 2021), and this strategy may not always lead to the desired effects in target companies (Davies & Van Wesep, 2018).

The fact that investors pay particular attention to their portfolio's carbon footprint has two important implications. First, the above results seem to empirically rule out the divestment hypothesis, discussed in Section 3. This is important because confuting this hypothesis implies that investors are systematically pricing carbon risk at the *firm* level (Hsu et al., 2020). In other words, investors are recognising that industry (Bolton & Kacperczyk, 2021a), and international diversification (Bolton & Kacperczyk, 2020), may not be sufficient when analysing carbon risk. Second, the results from above studies also emphasise the relevance of corporate governance as a parallel instrument to climate mitigation policies. In particular, investors' pressure on targeted companies may decrease the possibility of firms' regulatory arbitrage practices discussed in Section 4.1.2.

Furthermore, investors have also been engaging with firms to increase the amount and quality of climate-related information (Flammer et al., 2021). In fact, in the investor surveys by Ilhan et al. (2021a) and

Krueger et al. (2020) it is recognised that some kind of *underpricing* may be present in the equity market, as some studies in Section 3.1 confirmed (Hong et al., 2019). Additionally, institutional investors think that climate reporting may be the most effective way to increase market efficiency in pricing physical and transition risks (Ilhan et al., 2021a), ultimately increasing firm value, as empirically shown by Flammer et al. (2021) and Krueger (2015). However, these results should be compared with a survey conducted by Amel-Zadeh (2021), who discovered that, despite the fact that climate risks had a material impact on business operations, firms deliberately chose *not* to report climate risk information in their annual disclosure reports. In particular, this kind of information could result in proprietary costs for a company (Ilhan et al., 2021a).

This kind of empirical evidence has policy implications, such as in the need of a mandatory and standardised reporting set by the Task Force on Climate-related Financial Disclosures. However, this evidence should also be aligned with the theoretical debates in asset pricing literature. In a recent paper, Barahona et al. (2021) argued that in the extreme cases where investors cannot predict the future beta (i.e. the exposure) with respect to a certain risk factor, the resultant risk premium would be lower. They explained such a hypothesis because the impossibility to acquire such a factor loading will, in turn, render the formation of beliefs about an ex-ante risk premium difficult, thus lowering the hedging demand for that factor. Their work is in line with the study by Barnett et al. (2020) and Bourdeau-Brien and Kryzanowski (2020) and with the general idea that *ambiguity* (rather than *risk*) aversion, may shape the behaviour of investors toward climate change risks.

The argumentations made by Barahona et al. (2021) are of particular relevance for investors' expectations about physical risk. Specifically, the scant amount of disclosure needed by investors to measure their portfolios' physical risk exposure may be one of the reasons behind stock market behavioural biases and inefficiencies in pricing climate change dynamics (Hong et al., 2019; Huynh & Xia, 2021). Some studies found evidence that specific physical risks are embedded into stock price valuations (Balvers et al., 2017; Bansal et al., 2019). However, it is hard to believe that novel measures, such as climate indices (Hong et al., 2019), or satellite data (Ding et al., 2020), may have been the common tool investors have used to assess these risks at the firm level. The former point might be confirmed from the fact that 'alternative data' (to which weather data belongs) may have been historically an informational advantage proper of specific players in financial markets, such as hedge funds (Blank et al., 2019; Katona et al., 2018).

#### 4.2.3. *Timing considerations about climate change risk pricing*

Timing considerations are another critical point to integrate findings at the top-down and bottom-up level. First, it is important to understand how investors perceive climate risks today. Krueger et al. (2020) found that investors have been ranking climate change as the fifth most important risk in their investment process. Notably, policy risk seems to be the most important among the three risks related to climate change proposed in the survey (i.e. together with physical and technological risks). Similar results were found in the surveys by Amel-Zadeh (2021) and CFA (2020).

Additionally, it is relevant to grasp when investors expect climate risks will be financially material for the investment process. On this point, Krueger et al. (2020) showed that investors' responses differ with respect to the particular climate risk analysed. Investors think that policy risk has *already* begun to materialise, a result in line with the CFA (2020) survey. For instance, Atanasova and Schwartz (2019) showed that prices of oil firms are negatively related to their quantities of undeveloped reserves, consistent with the fact that investors have been recognising the possibility these assets may become stranded. However, responses to the surveys given by CFA (2020) and Krueger et al. (2020) showed that investors do not seem concerned about the possibility of a 'carbon bubble'. This result aligns with a study by Griffin et al. (2015), who showed a little equity response to the publication of scientific studies warning about the possibility of non-burnable carbon in the following decades. With respect to other types of climate risks, investor responses match the idea that the true effects of physical, technological and consumer demand risks will be more evident in the long run (Bansal et al., 2019). Specifically, Krueger et al. (2020), in line with Amel-Zadeh (2021) and CFA (2020) surveys, documented that physical risks will threaten the fate of the economy (and related investment decisions) in 5 to 10 years from now. Taken together, these results would indicate that the risk premium identified by Bolton and Kacperczyk (2021a) and Hsu et al. (2020) may reflect a *rational* reward investors require for greater exposure to climate mitigation policies.

Finally, it is important to understand when climate change risks *became* an important topic among the investment management community. In this regard, survey results also converge, indicating that most investors started to consider these risks few years ago. The last point has important implications for linking evidence with the asset pricing tests described in Section 3.1. First, this result could explain why studies in Table 1, that employ long-term estimation periods when applying asset pricing tests, found evidence of underreaction. The latter is more evident for physical risks (Ding et al., 2020), which, as shown by investor survey results, have received less attention than transition risks.

Second, these types of investor survey responses might also explain why most papers at the bottom-up and top-down levels have revealed that the response to climate change has been stronger over more recent estimation windows, thus supporting the recent market concerns about these risks (Painter, 2020). Specifically, Bansal et al. (2019) found that the temperature elasticity of equity valuations had increased over the years, but such a result does not hold when lower frequencies are considered (as in Griffin et al. (2019)). Alok et al. (2020) and Dessaint and Matray (2017) documented that the salience bias of managers tends to decrease over time, meaning that managers *learn* that extreme weather events effects are not detrimental to how they may think. These outcomes should be read in combination with the recent literature that has shown investors' beliefs to align with both climate mitigation policies proposals and the information disseminated by the scientific community about climate-related topics. This result has been found not only in the (i) real estate market (Baldauf et al., 2020; Bernstein et al., 2019), (ii) municipal bond market (Painter, 2020), (iii) or derivative market (Kruttli et al., 2021; Schlenker & Taylor, 2021), (iv) but in the stock market as well (Anttila-Hughes, 2016; Griffin et al., 2015; Huynh & Xia, 2021; Sautner et al., 2021). Notably, such alignment may explain why some arbitrage opportunity has decreased in value in recent years, as Jiang and Weng (2019) found.

Finally, the fact that concerns about climate risks are a recent phenomenon in financial markets has implication for the *sign* of the climate risk premium. Equilibrium models like the one proposed by Pástor et al. (2020) imply that a portfolio of assets hedging climate risks should have a negative premium on an ex-ante basis. However, if investors' began to price these risks only recently, this would imply that the magnitude of unexpected return may dominate over ex-ante considerations about climate risk premiums. These observations should be considered when evaluating the superior performance of sustainable strategies described in Section 3.1.3 over short horizons. In particular, one would conclude that assets providing a hedge to climate risks, such as green stocks, carry a positive (and thus incorrect) climate risk premium (Pástor et al., 2021). Moreover, as the equity market learns how to price climate risks over time, the outperformance of green stocks may be rarely observed in the future.

## 5. Conclusions: Current gaps and insights for future research in climate finance

The field of climate finance is new, and the growing interest in the political and industrial debate in recent years has boosted research in this field (Hong et al., 2020). In the near future, collaboration between academics and, in particular, interdisciplinary research could strengthen the knowledge base on how climate risks pose a serious threat to society and, to a greater extent, a systematic risk for financial markets (Barnett, 2017; Battiston et al., 2017; Campiglio et al., 2018; Dietz et al., 2016; Karydas & Xepapadeas, 2019). Following the quantitative results of climate finance studies at the top-down and bottom-up levels, this work reviewed how climate risks may affect the cross-section of stock returns, exploring various economic, rational, and behavioural channels. The evidence provided in this review enriches the climate finance agenda with the following important points.

First, several works analysed in Section 4.2 showed that climate risks assessment by both retail and institutional investors has not always been driven by fundamental information (Alok et al., 2020; Choi et al., 2020; Dessaint & Matray, 2017). However, it was also demonstrated that the response to these risks in different asset classes has been stronger over more recent estimation windows, highlighting rising market concerns about climate change risks (Huynh & Xia, 2021; Painter, 2020). Thus, an interesting topic in climate finance would be to investigate *why* and to what extent the profitability of certain anomalies documented in Section 3.1 has changed over time (Black, 1993). A possible 'alpha decay' (Kuenzi, 2019) in climate-related strategies because of a shift from investor attention into awareness may formalise the channels investors are using to correct the mispricing of climate change risks in financial markets. Furthermore, this type of information would be of utmost importance in the formation of hypothesis aimed to develop the equilibrium models introduced in Section 3 (Giglio et al., 2020).

Second, because climate finance literature is in the early stages, further research is needed to better integrate certain patterns from the meteorological field, especially with respect to extreme weather events and multi-hazard relationships (Pescaroli & Alexander, 2018). Empirical evidence provided by the event studies in Section 4 showed contradictory results about the impact of climate-related disasters on certain portfolios' returns (Lanfear et al., 2019). A critical point in meteorological research is that these kinds of events may become more frequent in the future (Raymond et al., 2020). Such concerns, combined with a lack of consensus in the financial research, open further avenues of study in the climate finance literature, especially for asset allocation purposes. Because some of these events may be predicted using climate models (Raymond et al., 2020), a more granular usage of asset-level data could provide better ways to dynamically optimise portfolios across climate-related hazards in certain areas. In particular, a portfolio of assets whose returns respond to specific extreme weather events could be rebalanced according to the signal of climate models before a 'disaster' occurred (Grindsted, 2020). The hedging portfolio developed by Engle et al. (2020) does not distinguish between different types of climate change news. This opens avenues for future research in climate finance aimed to construct better hedging tools against physical risks, from which both firms and investors would benefit.

Finally, as emphasised elsewhere in this review, few studies have investigated the ways in which firms can adapt to climate change risks. Clearly, the dissemination of climate-related anomalies is important in driving the fair assessment of climate risks in financial markets, but the development of adaptation measures at the firm level is no less important. The heterogeneity in adaptation capacities across firms provides a natural groundwork to investigate the presence of an adaptation premium in the cross-section. This review highlighted certain firm-level characteristics that could hinder investment strategies geared toward climate change risks, such as financial constraints (De Haas et al., 2021; Xu & Kim, 2021). However, the adaptation capacities of firms may be further compromised by (i) investors' preferences for green assets, which may result in a higher cost of capital for brown firms (Pástor et al., 2020); or (ii) the process of updating financial market beliefs regarding physical risks (Choi et al., 2020; Makridis, 2018; Pankratz & Schiller, 2021). Future research aimed to investigate how these complex dynamics should affect equilibrium asset returns would be valuable.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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