Physical Climate Risk and Firms' Adaptation Strategy*

Xia Li

Questrom School of Business, Boston University

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Abstract: Physical climate risks increasingly impact firms. While scholars have studied how firms adapt to short-term shocks and business cycles, we know little about how firms adapt to climate change, which is long-term, systemic, and irreversible. I build a novel dataset that compiles information on the adaptation strategies of publicly traded companies across the globe and merge it with climate science data. Using this dataset, I examine whether, how, and under which conditions firms adapt to physical climate risks. I find that the average adaptation rate across firms and climate risk drivers is just 23 percent. Firms facing higher climate risks are more likely to adapt and do so with a broader range of adaptation strategies. Firms with better environmental and social performance ratings are more responsive to climate risk. I also explore the mechanisms and find that higher climate risks increase firms' risk perceptions, and it is likely that firms with better environmental and social performance have superior adaptive capabilities.

Keywords: Adaptation, Strategy, Climate Change, Environmental, Social, and Corporate Governance (ESG)

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INTRODUCTION

From American utilities to Australian builders, from Asian manufacturers to European winemakers, companies face increasing physical climate risks – that is, risks arising from the physical effects of climate change.[1] In particular, climate-related extreme weather events (such as wildfire and floods) damage firms' properties and disrupt operations. For example, catastrophic wildfires worsened by climate change led to billions of dollars in damages and liabilities to utilities such as PG&E (Wall Street Journal 2019a).[2] More gradual changes (such as water and heat stress) affect firms' resource availabilities and reduce their productivities. For example, the rising temperature has increased the cooling cost in Google's energy-intensive data centers (New York Times 2019a) and caused substantial labor productivity loss (The Australia Institute 2020; Zandar et al. 2015).[3] In addition to these direct impacts, increasing physical climate risks also impact firms indirectly, e.g., through increased insurance premiums and cost of debt (Kling et al. 2021; Wall Street Journal 2018). Globally, insurance losses from weather-related events increased from an annual average of $10 billion in the 1980s to more than $65 billion in the 2010s (Aon 2021; Munich Re 2017). Moreover, it is estimated that about $7.2 trillion of Moody's rated debt, around 10% of the total, has high exposure to physical climate risks that could substantially affect the fixed-income market (Bloomberg 2021).

Faced with these inevitable and irreversible threats (IPCC AR6, 2021), it is important for firms to adapt, as the essence of strategic management is adapting to external changes to ensure the survival and growth of firms (e.g., Ander and Helfat 2003; Chakravarthy 1982; Gulati, Lawrence and Puranam 2005; Levinthal 1997; Sarta, Durand and Vergne 2021).[4] Yet, most research on firms'

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[1] Climate risk includes physical and transition risks. This paper focuses on physical climate risks, and climate risks refer to physical climate risks for simplicity unless otherwise specified.

[2] Other examples include the disruption of supply chains (e.g., of Toyota and Honda) in Southeast Asia due to increased flooding (Nikkei Asian Review 2018); oil and gas fields in Russia being at risk from thawing permafrost (Bloomberg 2019); and the disruption of the global shipping industry due to floods in Germany and China in 2021 (CNBC, 2021).

[3] Other examples include the closing of Coca-Cola plants in India due to water shortage (CNBC 2014); wine producers facing hotter summers and warmer winters that stem from climate change (New York Times, 2019b); the devaluation of homes in Florida by $30billion to $80 billion, or 15 to 35%, by 2050 due to sea level rise (MGI, 2020).

[4] In recent years, firms have been facing increased shareholder activism to disclose and manage their climate risk exposure (Ceres 2020b; Flammer, Toffel, and Viswanathan 2021; Financial Times 2020; Krueger, Sautner, and Starks 2020).

adaptation to external changes has focused on innovation in response to business cycles (Aghion et al 2012; Anand and Singh 1997; Fabrizio and Tsolmon 2014), market entry in response to technology changes (Adner and Helfat 2003; Eggers and Kaplan 2009); or investments in key strategic resources in response to short-term shocks such as financial market crisis (Flammer and Ioannou 2021). Little is known about firms' adaptation strategies when facing systemic, long-term, and irreversible crises such as climate change, which is fundamentally different from those short-term or cyclical changes. In this study, I examine whether, how, under which conditions firms adapt to physical climate risk.

A priori, it may appear that firms would have the necessary foresight and pursue adaptation strategies as an obvious preventative measure since adaptation helps firms reduce business interruptions, increase operational efficiency, and explore innovative opportunities (Amit and Wernerfelt 1990; Eggers 2012; Helfat and Martin 2015; Tashman and Rivera 2016). For instance, Starbucks develops coffee plants and growing practices that are more resistant to warmer temperatures (Reinhardt and Toffel, 2017). However, several factors might hinder companies from adapting to climate risks. First, firms may not have the capacity to fully evaluate the physical impacts of climate change as it is forward-looking and cannot be easily calculated using historical data (Battiston and Monasterolo 2020; Berkout 2012). Second, adaptation strategies can be costly and may compete with alternative projects that might otherwise be pursued. Third, climate risk is long-term, and lies beyond the time horizon of most managers and business cycles (Bansal et al., 2018; Carney, 2015; Flammer et al., 2021; Grodal and O'Mahony, 2017; Wright and Nyberg, 2017). As such, the upsides of adaptation tend to materialize in the long run, while the downsides (e.g., adaptation cost) tend to manifest in the short term. As a result of these factors—and given that individuals (including managers) are usually myopic and favor short-term rewards over long-term ones (Flammer and Bansal 2017; Holmstrom 1999; Stein 1988)—firms may tend to underinvest in adaptation strategies *even if* pursuing such strategy would pay off in the long term. For instance, despite the known sea-level rise risk in Miami, real estate developers keep building with few climate change adaptation measures (Ariza, 2020).

While the above factors may impede some managers from investing in climate adaptation strategies, I expect the level of climate risks to likely play an important role in managerial decision-making. For example, firms facing higher climate risks are more likely to experience increased direct impacts of climate change, which increases firms' risk perception of this irreversible long-term shock. This increased risk perception, in turn, may lead firms to re-evaluate the up-and downsides of adaptation and induce them to consider investing in adaptation strategies. Further, some firm characteristics, such as their environmental, social, and corporate governance (ESG) performance, can also influence firms' adaption to climate risk. Firms with better ESG performance may have higher perceptions of climate risk and superior adaptive capabilities to respond to environmental and social challenges.

In this study, I explore these relationships empirically. It is difficult to measure both physical climate risks and firms' adaptation strategies. The assessment of firms' physical climate risks requires climate science to conduct a forward-looking analysis, as climate risks cannot be simply calculated based on historical weather data (Dell, Olken, and Jones 2014; Hsiang 2016; Li and Gallagher 2022). Measuring adaptation is also challenging because firms can take a broad range of adaptation strategies in response to different climate risk drivers, and these strategies cannot be easily translated into one single quantitative measure. Novel data is needed to overcome these challenges. To measure corporate physical climate risks, I collect and use climate science data based on geospatial, historical, and projection models developed by Four Twenty Seven (a Moody's affiliate). To measure firms' adaptation strategies, I hand-code the climate disclosure text that publicly traded companies reported with CDP (formerly, the Carbon Disclosure Project) between 2011 and 2017. I merge the disclosed adaptation data with physical climate risk data at the firm-climate risk-year level. The final sample covers 1,068 public companies headquartered in 43 countries, and their adaptation to five climate risk drivers: heat stress, water stress, sea-level rise, floods, and hurricanes/typhoons. To the best of my knowledge, this is the first longitudinal database that measures firms' adaptation strategies in response to different climate risk drivers. The firm-climate risk-year data allows me to examine how firms adapt to different levels and types of climate risks over time.

The empirical results paint a nuanced picture of firms' adaptation strategies across countries and industries. I start by documenting a series of stylized facts pertaining to firms' disclosed adaptation strategies of their direct operations. It turns out that most firms don't adapt to most climate risk drivers. The average disclosed adaptation rate across firms and climate risk drivers is just 23 percent. When examining what type of adaptation strategies firms pursue, I find that firms are more likely to engage in operational as opposed to business strategies (i.e., those associated with firms' core businesses such as capital expenditure, land, innovation, and workforce).

Further, I examine how firms adapt to physical climate risk. I find that firms facing higher levels of climate risks are more likely to adapt and do so with a broader range of adaptation strategies. Because the data capture variation within firm across different types of climate risk, I am able to estimate models with firm fixed effects, which control for unobserved factors that make some firms more likely to adapt in general. The results are statistically significant both in the cross section, and within firm between climate risk drivers, which indicates that managers are responding to the specific types of risk that the Four-Twenty Seven climate models are most salient for individual firms. Also, the impact of climate risk on business strategies increases over time, but I don't find a similar trend for operational strategies. Moreover, I examine under which conditions firms are more likely to adapt, and find that firms with better ESG performance are more responsive to higher climate risks. The influence of ESG is driven by firms' environmental and social performance, not their corporate governance.

The contributions of the paper are as follows. First, this paper contributes to the literature on firms' adaptation to external changes. While previous studies focus on short-term or cyclical changes such as industry cycle, technology shock, and financial crises (Aghion et al. 2012; Anand and Singh 1997; Eggers and Park 2018; Flammer and Ioannou 2021), this study explores a fundamentally different change by examining whether and how firms adapt to long-term, systemic, and irreversible crises such as climate change. Specifically, I develop a novel dataset that compiles information on the adaptation strategies of publicly traded companies across the globe, merge it with climate science data, and use the dataset to examine the impact of different levels and types of climate risks on firms' adaptation strategies. I follow Helfat's (2007) recommendations to explore the facts and document the important phenomena in the hope that it will stimulate both disciplinary and interdisciplinary research in this area.

Second, by examining firms' adaptation to climate change as opposed to their climate mitigation efforts, this study advances our understanding of firms' relationship with the environmental system. Extant literature on climate change has primarily focused on firms' climate change *mitigation* strategies, the decrease of the firms' impact on the environment (Bolton and Kacperczyk 2020; Dowell, Lyon and Pickens 2020; Hart and Dowell 2011; Jira and Toffel 2013; Krueger 2015). In contrast, research on firms' climate change *adaptation*, strategies firms pursue to address the impact of the changing environment on firms, has been called for by scholars but remains sparse (Engle et al 2020; Frankhauser 2017; Flammer et al. 2021; Linnenluecke et al. 2013).[5] The most closely related work includes case studies (Canevari-Luzardo et al. 2020; Hamann et al. 2020; Linnenluecke, Stathakis, and Griffiths 2012) and conceptual frameworks (Berkhout 2012; Clement and Rivera 2017; Winn et al. 2011) on climate change adaptation. This study moves beyond the previous work and explores firms' various adaptation strategies to different climate risk drivers across industries and countries comprehensively.

Third, this study contributes to the extant literature by examining how firms' ESG performance interacts with market strategies (such as adaptation). While previous studies have either focused on the impact of ESG on firms' competitiveness and profits (Flammer 2015; Hart 1995; Hawn and Ioannou 2016; King and Lenox 2002; McWilliams and Siegel 2001; Ruf et al.

[5] Most studies on adaptation economics are at the country or regional levels (see surveys Kahn 2016; and Massetti and Mendelsohn 2015). There are also some studies on individual behaviors or perceptions on climate change in response to extreme weather events (e.g., Demski et al 2017).

2001), or how firms respond to business, political, and financial risks (Barlevy 2007; Bloom and Milkovich 1998; Delios and Henisz 2000; Oh and Oetzel 2011), they are usually discussed separately. In this study, I examine how firms' ESG performance can positively influence firms' adaptation strategy.

Finally, this paper contributes to the sustainability literature by using and developing novel datasets to measure firms' climate risks and adaptation strategies. Specifically, I use the novel data from Four Twenty Seven which forecasts firms' climate risk levels based on locations of firms' facilities across the globe and climate modeling. Also, I develop adaptation data by hand-coding textual information of the firms' disclosed adaptation from CDP. To the best of my knowledge, it is the first longitudinal database on firms' climate risk adaptation strategies in response to different climate risk drivers.

FRAMEWORK OF PHYSICAL CLIMATE RISK AND ADAPTATION STRATEGY

Physical Climate Risk

Climate risks, or climate change risks, refer to the risk assessments based on analyzing the consequences of climate change.[6] Climate risks include two major categories: physical climate risks and transition climate risks (Bolton and Kacperczyk 2020; CDP 2016; MGI 2020; TCFD 2017). Physical climate risks are risks arising from the physical effects of climate change, such as wildfire and sea-level rise. Transition risks refer to the risks of transitioning to a low-carbon economy, such as regulatory risk, technology risk, market risk, and reputational risk (TCFD 2017). Physical climate risks tend to materialize over the longer term, while transition climate risks typically span a shorter time frame (Krueger et al. 2020). While both physical and transition climate risks are important, this study focuses on the impact of physical climate risks.

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[6] While the differentiation between risk and uncertainty in economics (Keynes 1936; Knight 1921) is fully appreciated, climate risks usually include "uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large" (IPCC 2014). Kunreuther et al. (2013) discuss incorporating uncertainty into climate risk management.

Physical climate risks (henceforth "climate risks") include a wide-scale and scope of risks (Gasbro and Pinkse 2015). These risks are caused by different drivers, including water stress, heat stress, excess rainfall, sea-level rise, wildfire, hurricane, and typhoons. These climate risk drivers can be divided into two broad types: 1) acute climate risks, which are associated with increased frequency and severity of one-off, discontinuous extreme weather events such as floods or hurricanes;[7] and 2) chronic climate risks, which impacts on gradual shifts in climate parameters such as temperature rise and water stress (TCFD, 2019).

Climate risk is long-term in nature and may extend beyond the time horizons of most managers and business cycles (Bansal et al. 2018; Carney 2015; Flammer et al. 2020; Grodal and O'Mahony 2017; Wright and Nyberg 2017). It is systemic and impacts different sectors from manufacturing to finance (Europe Central Bank, 2019; Financial Stability Board, 2020). Moreover, the impact of climate risk is irreversible (Solomon et al. 2009). The world is likely to reach 1.5C of warming by 2040 in a best-case scenario of deep cuts in GHG emissions (IPCC AR6 2021). Even if GHG emissions were to stop completely, the planet will continue to warm for two or three more decades, as many GHGs stay in the atmosphere for more than a century (IPCC 2014; Farber 2007; Myles et al 2009; Matthews et al 2018; Stern 2006). The long-term, systemic, and irreversible features make climate risk fundamentally different from other short-term or cyclical changes such as technology shocks or financial crises, and should ultimately have a profound impact on firm strategies.

Climate Change Adaptation Strategies

Faced with climate risks, firms can seek to *mitigate* and *adapt* to climate change.[8] Climate change mitigation addresses the *causes* of climate change and focuses on greenhouse gas (GHG) emissions reduction. Examples include shifting to renewable energy, increasing energy efficiency, and carbon

[7] Note that although climate risks are associated with some natural catastrophe risks such as floods and hurricanes, not all natural catastrophes are related to climate risks. For instance, earthquakes, volcanos, and tsunamis, while potentially devastating, are not impacted by climate change.
[8] The Paris Agreement on Climate Change called for action on both climate change mitigation and climate change adaptation - https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, accessed in August 2021.

capture and storage. Climate change *adaptation*, in contrast, focuses on adjustment to climate and its effects and addresses the *consequences* of climate change. For instance, some Champagne companies in France have invested in English vineyards as the Champagne region has warmed (New York Times 2019b). This paper focuses on firms' climate change adaptation.

Climate change adaptation (henceforth "adaptation") is the "process of adjustment to actual or expected climate and its effects" (IPCC 2014) to moderate the negative and/or enhance the positive impacts of climate change. Firms can take several measures – ranging from insurance and business continuity plans to innovation and Mergers & Acquisitions (M&As) – in response to the same climate risk driver. Also, firms' adaptation to different climate risk drivers may vary. For instance, a firm might adopt energy-efficient technologies in response to heat stress while relocating its assets when facing sea-level risk. In this paper, firms' adaptation strategy is defined as a combination of different adaptation measures in response to various climate risk drivers to pursue firms' strategic objectives.[9]

Firms' adaptation strategies can be categorized into different types. For instance, firms can respond to climate impacts and adopt operational strategies to assess, reduce, or transfer climate risks. For example, when facing sea level rise risk, firms may assess their risk profile, secure backup power generators, purchase insurance, or create a business continuity plan. These strategies enable firms to develop operational capabilities to carry out routine activities (Nelson and Winter, 1982) or maintain business as usual (Scott 1981). Firms can also adapt by pursuing business strategies, i.e., choices associated with firms' core assets and activities, such as capital expenditure, land, innovation, and workforce. This involves building or reconfiguring internal and external competencies (Teece et al. 1997), modifying firms' boundaries (Scott 1981), or shifting to a new mode of management (Clement and Rivera 2017; Finz 2013; Hannah et al. 2013; Scott and McBoyle 2007). For example, when facing heat stress, firms may innovate or adopt new

[9] In this paper, the definition of firms' adaptation strategies is broad. It includes resilience-building measures, i.e., firms' capacity to "absorb the impact and recover from drastic environmental change associated with weather extremes." (Linnenluecke, Griffiths, and Winn 2012).

technologies that use less energy for cooling, develop crops that are more resilient to warmer temperatures, or diversify their locations. Compared to operational strategies, business strategies enable firms to create dynamic capabilities in response to a changing environment (Berkhout et al. 2006; Collis 1994; Teece and Leih 2016) and typically require more resources (Rajagopalan and Spreitzer 1997), including money and time input.

The Impact of Climate Risk on Firms' Adaptation Strategy

Despite increased climate change exposure and the need to adapt, it is not a given that firms will adapt to climate risks. Rather, adaptation is a decision based on cost-benefit calculation, as well as a complex process that involves perceiving the impacts of climate risks and making changes over time.

On the one hand, adapting to climate risks provides companies with several benefits. Changes in the natural environment negatively affect firm operations through disruptive events that cause damage to property and disruption to supply chains, and also gradual impacts that reduce firms' resource availability and labor productivity. Accordingly, adapting to climate risks can firms reduce production costs and increase operational efficiency (Amit and Wernerfelt 1990), establish alternative sources subject to less uncertainty (Tashman and Rivera 2016), explore innovative opportunities (Eggers, 2012), and improve competitive advantage (Helfat and Martin 2015). For example, Juniper Networks migrated part of its headquarter labs from Sunnyvale to Quincy to reduce the impact of sea-level rise on its operations. Sumitomo Chemical has developed chemical agents that enhance the ability of plants to withstand heat stress and drought.

On the other hand, several factors may inhibit firms from adapting to climate risks. First, the signs of climate change might be ambiguous and sometimes can hardly be differentiated from normal variations in weather (Barnett 2001; Berkout et al. 2007; Weinhofer and Busch 2013). Anecdotal evidence suggests that while firms generally respond to extreme weather events when they have experienced the impact of events directly, they may not attribute these events to climate change. Thus, they do not initiate climate-related actions after these events have been resolved.[10] Second, firms may not have the capacity to fully estimate the physical impacts of climate because they are forward-looking and uncertain, and cannot be easily calculated based on historical data (Battiston and Monasterolo 2020; Berkout 2012). Given the ambiguity and uncertainty of climate risks, managers may rely on heuristics that are biased toward maintaining the status quo or under-preparation for incidents (Dessaint and Matra 2017; Meyer and Kunreuther 2017). Third, climate risk has a broad scope, and firms may not be capable of adapting to all climate risk drivers as it is costly (Fankhauser et al. 1999; Kelly and Kolstad 2005). Some business strategies (such as innovating climate-resilient technologies and relocating firm facilities) require substantial resources and may compete with other operational and strategic objectives. Also, some firms may try to put the cost of adaptation on other parties such as governments. For instance, some coastal real estate developers may expect government property buyouts (Keeler et al 2022).

In addition to the various factors influencing the cost-benefits analysis of climate risk adaptation, managers' temporal preferences and time horizon can influence their decision-making. Specifically, many managers' time horizon is likely to be shorter than the time horizon of climate change. There is evidence that managers tend to be myopic and favor investments that pay off in the short run at the expense of long-term investments (Flammer and Bansal 2017; Holmstrom 1999; Stein 1988). Accordingly, *even if* climate risk adaptation's (long-term) benefits are substantially higher than the cost, firms may not pursue adaptation strategies.

Although it is not obvious that each firm will adapt to every climate risk that it faces, it is still reasonable to expect that the level of climate risks factors into firms' decision-making process. Managers rarely have complete information about firms' climate risks. Thus, they tend to base their climate strategies on incomplete data, and are forced to change tactics as more information comes to light (Dessaint and Matray 2017). Firms facing more significant climate risks are more likely to

[10] For example, as disclosed in the CDP report, one utility company in the U.S. responded to natural disasters such as drought through risk management procedures, but claimed that "we cannot predict whether long-term changes in frequency of severe weather events due to climate change will have more of an impact on the electric distribution infrastructure than normal year to year variations in severe weather events."

experience increased frequency and severity of extreme weather events or more significant gradual climate impacts in the short term, which can cause damages to property, business interruptions, or other financial consequences. For example, firms with high water stress are likely to have experienced a reduction in water supply, which could increase water input costs, or in extreme cases, result in water supply failures. These events provide salient information on climate impact to managers, reveal the consequences of investment myopia, suggest that the benefits of adaptation can be short-term and pressing, and increase firms' risk perception of this irreversible long-term shock. At the individual level, climate change perception influences individuals' behavior and property values (Baldauf, Garlappi, and Yannelis 2020). At the firm level, the increased climate risk perception, driven by higher climate risk, can also lead firms to re-evaluate the up-and downsides of adaptation, reconsider firm strategies, and ultimately lead them to invest in adaptation strategies. Combining these insights, I expect that increased climate risks can stimulate firms' adaptation strategies:

H1: Firms facing higher physical climate risks are more likely to initiate adaptation strategies.

While I hypothesize a positive relationship between higher climate risk and increased firms' adaptation strategies, not all firms adapt (more) when facing higher climate risks. In the following section, I explore internal conditions under which firms are more likely to adapt to climate risks, including firms' ESG performance.

ESG and Firms' Adaptation to Climate Risk

Firms' environmental and social performance refers to a firm's engagement in activities that are in response to stakeholder pressure or demand for emissions reduction, workforce diversity, community involvement, and other environmentally and socially responsible practices (Cao, Liang, and Zhan; Flammer 2013; Neumann, Cennamo, Bettinazzi, et al. 2013, Waddock 2008,). As firms' environmental and social performance and their adaptation to climate change have different objectives and respond to different risks and stakeholders, they may compete for firm resources.

However, because climate risk is about the change of the natural environment and has social impacts, I argue that firms' environmental and social performance can facilitate firms' adaptation strategies.

First, firms with better environmental and social performance are likely to have higher climate risk perceptions. These firms can be more sensitive to stakeholders' concerns on environmental and social issues and thus pay more attention to climate change. Firms' choice of adaptation is not only driven by objective climate risk, but also influenced by subjective factors such as climate change awareness and belief (Arnell and Delane 2006; Dowell et al., 2021; Gasbarro and Pinkse 2015; Hoffmann et al. 2009; Linnenluecke and Griffiths 2010). Although most stakeholder concerns focus on climate change mitigation, such as GHG emissions reduction, energy use, and renewable energy development, they may spill over to related dimensions such as physical climate risk and adaptation. Firms' overall attention to climate change is likely to correlate with climate risk perceptions and thus motivate them to search for ways to adapt. Also, firms with better environmental and social performance are more likely to be longer-term oriented (Eccles, Ioannou, and Serafeim 2014; Flammer and Bansal 2017). In turn, they may put more weight on the long-term impact of climate change, see more connections of climate risks with current firm strategies, and perceive climate risks with higher impact and likelihood. This increased climate risk perception can increase firms' sensitivity to higher climate risks and stimulate adaptation strategies.

Second, firms with better environmental and social performance are more likely to have organizational resources and dynamic capabilities (Eggers and Kaplan 2009; Halfat and Martin 2015) that enable them not only to manage their environmental and social impacts well, but also to better adapt to the external environmental changes. Superior environmental and social performance yields multiple benefits and makes other assets more valuable (Hart 1995; Hawn and Ioannou 2016; Siegel and McWilliams 2011). It also helps firms to maintain and enhance their competitiveness after external changes (Flammer and Ioannou 2021). For instance, better environmental and social performance improves firms' human resource capabilities (Brekke and Nyborg 2004), strengthens connections with local communities (Tilcsik and Marquis 2013), encourages knowledge-sharing with suppliers (Dyer and Singh 1998), promotes favorable access to local infrastructure (Fombrun 1996), and increases innovation capability (Flammer and Kacperczyk 2016). These capabilities, which are developed from firms' environmental and social impact management, have synergies with firms' adaptive capabilities and can help firms adapt better when facing higher climate risks.

On top of environmental and social performance, corporate governance can also influence firms' tendency to adapt. Firms with good corporate governance aim to align managers' interests with shareholders to increase long-term firm value and exert better board oversight of their company's risk management (Adams 2012; Gupta and Leech 2014), which can include climate risk. Accordingly, firms with better corporate governance are more likely to assess the climate impacts, and initiate strategies to adapt to climate change.

In sum, firms with better ESG performance are likely to have higher perceptions of climate risk and superior capabilities to respond to the environmental challenges. Hence, I expect that firms with better ESG performance are more likely to adapt when facing higher climate risk.

H2: Firms with better ESG performance are more likely to adapt to higher climate risks.

In what follows, I take these hypotheses to the data, and examine empirically whether, how, and under which conditions firms adapt to climate risks.

DATA

Physical Climate Risks

The assessment of firms' physical climate risks requires climate science to conduct a forward-looking analysis, because climate risks cannot be derived from historical weather data alone (Dell, Olken, and Jones 2014; Hsiang 2016; Li and Gallagher 2022). In this study, I collect firms' climate risk data from Four Twenty Seven, an affiliate of Moody's. Four Twenty Seven examines the degree and extent of climate change exposure based upon geospatial, historical, and projection models. It uses the period of 1975-2005 as a historical benchmark, projects future states in 2030-2040 under the "Business as Usual" scenario, and gets a basis of how climate is expected to shift over time at a given location by comparing future projections against the historical baseline. The criteria for the analysis include detailed climate risk projections that measure the relative degree of change in extreme events such as intensity and frequency of rainfall, high temperatures, historical cyclone activity, coastal flooding, and water stress.

In these data, a company's physical climate risks are linked to the firm's direct operation, supply chains, or markets. This study focuses on the climate risks of firms' direct operations.[11] Four Twenty Seven evaluates the climate risks of a company's direct operations by aggregating the climate risks of all its operational facilities—ranging from manufacturing sites and warehouses to offices and retail facilities. Facilities that are being developed and not yet operational are not included. The global database of corporate facilities comprises over 1 million sites, sourced from several public and private industry sources, and mapped to the corporate owner.

To measure the magnitude of various climate risks of firms' activities, Four Twenty Seven assigns a series of sensitivity factors to the facilities based on the nature of their activities. These factors vary by climate risk driver, reflecting the sensitivity of the company's activities to the corresponding risk factor. For example, a thermal power plant is more sensitive to water stress than an office because it requires much water for cooling. As a result, a power plant will receive a higher water stress score than an office in the same area.

Four Twenty Seven translates raw indicators of physical climate risk exposures into a standardized score ranging from 0 to 100. Higher climate risk scores indicate higher climate risk exposure. The data are at the firm-by-climate-risk level. They comprise 2,233 public companies

[11] As detailed in Appendix A, both supply chain and market climate risks are evaluated at the country or industry level by Four Twenty Seven. Thus they do not provide the same level of details as those provided by climate risks of firms' direct operations, which are based on facility information and disaggregated into different climate risk drivers. Also, the data on adaptation strategies are centered on those responding to climate risks of firms' direct operations.

headquartered in 47 jurisdictions,[12] and cover more than 1 million facilities located in 200 countries and 10 Standard Industrial Classification (SIC) groups. The data include the assessment of several climate risk drivers, namely heat stress, water stress, sea-level rise, floods, and hurricanes/typhoons. Online Appendix A provides more methodological details for different climate risks.

Disclosed Climate Change Adaptation Strategies

Measuring firms' adaptation to climate change is complex. First, firms can take different adaptation strategies in response to the same or different climate risk drivers (e.g., firms can adopt energy efficiency technologies in response to heat stress while relocating their assets when facing sea level rise risk). Second, the different adaptation strategies cannot easily be compared and translated into one single quantitative measure (climate change mitigation, in contrast, can usually be translated into quantities of carbon emission reductions).

To overcome measurement difficulties, I use firms' disclosed adaptation to approximate firms' adaptation strategies and manually code the disclosure data. I obtain firms' climate disclosure reports from CDP.[13] Every year public firms provide comprehensive information on their climate risks and management methods in response to a survey from CDP, mainly driven by pressures from investors (Kolk, Levy, and Pinkse 2008). These surveys collect information about firms' physical and transition climate risks, climate change opportunities, GHG emissions, and firms' climate change mitigation and adaptation strategies. The sample period consists of 2011–2017, the time frame during which the CDP survey consistently asked about climate risk information.[14]

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[12] Four Twenty Seven data cover most large public companies. For instance, the 2019 climate risk data cover 94% of S&P 500 companies. 83% of the companies in the dataset are multinational companies.

[13] Scholars have used CDP data to analyze firms' climate and environmental strategies (e.g., Flammer et al. 2021; Kim and Lyon 2007; Kolk and Pinske 2007; Lewis, Walls, and Dowel 2014; Reid and Toffel 2009).

[14] CDP changed the questionnaire in 2011 and 2018. Accordingly, I did not include the years prior to 2011 and after 2017. In 2017, CDP sent the questionnaire to over 6,000 companies, covering all S&P 500 companies, and received responses on physical climate risks and adaptation strategies from 2,003 companies.

I read through all firms' disclosed adaptation strategies in CDP reports and performed two rounds of intensive manual text coding. The first round consists of inductive coding of 1,000 firms' disclosed adaptation activities in 2017, and is used to generate a list of 23 categories of adaptation strategies.[15] For example, JBS "seeks to assume advance purchases of financial derivatives contracts to purchase agricultural commodities," and I code it as *Risk Transfer*. Rolls-Royce "innovated more efficient products such as the Trent XWB engine, which is designed with consideration for likely changes in physical climate parameters such as increasing temperature," and I code it as *Innovation*. Three researchers coded the firms' disclosed adaptation measures into different categorizations, and the interrater agreement was above 95 percent. The coding, definition, and examples of different categories of adaptation are detailed in Table B.1 in Appendix B.

The second round consists of using this list of categories to code the remaining firms and years. I code a category equal to 1 for a firm that discloses adaptation to a climate risk driver in a specific category and equals 0 if not. I iterate this process for each category, and the final outputs comprise 23 scores for each firm and each climate risk in each year. For firms that don't disclose any adaptation to specific climate risk drivers, I fill in all categories as zero. Some firms don't disclose climate-related information in certain years (i.e., not all firms disclose climate information consistently from 2011 to 2017). As I don't know why some firms opt-out in certain years, I treat these cases as missing data instead of assuming them as 0.

As for most corporate disclosures, firms' disclosed adaption in CDP may not accurately reflect their actual practices as there might be selective disclosures such as "greenwash" or "brownwash" (Callery and Perkins, 2021; Kim and Lyon 2014; Lyon and Maxwell 2011). However, the selective disclosure possibilities of adaptation are likely lower than firms' environmental practices. Unlike *firms' impact on the environment*, there are no regulations on how firms *adapt to*

[15] These categories include risk assessment, risk management, risk transfer, supplier management, enterprise risk management, buffer, other operational measures, hard technology adoption, soft technology adoption, climate-specific study, resilient input, product diversification, market diversification, location diversification, spinoff and M&A, innovation, relocation, stakeholder engagement, energy management, water management, substitute, eco-based-adaptation, and other strategies.

the changing environment such as climate risks.[16] As such, firms' inadequate adaptation measures are not likely to trigger immediate regulatory risk the way poor management of toxic emissions does. Also, as most environmental rating agencies had not incorporated firms' physical climate risks and their adaptation measures into the rating scope by 2017 (the last year of the sample period), firms don't have incentives to use linguistic tactics in disclosing their adaptation strategies to influence environmental ratings (Kim and Fabrizio 2019). As shown in Figure 1, the percentage of disclosed firm adaptation across climate risk drivers is less than 30%. Also, for 32% of firm-climate risk drivers, firms disclose their climate risks but do not report adaptation measures with CDP. [17]

Other Data Sources

To measure firms' ESG performance, I collect data from MSCI ESG STATS (formerly known as the Kinder, Lydenberg, and Domini (KLD) database), which are the most comprehensive ESG scores used in the literature (e.g., Cao et al. 2019; Chatterji, Levine, and Toffel 2009, Flammer 2015). I also collect alternative ESG ratings from Refinitiv (ASSET4) and Sustainalytics in lieu of the MSCI ESG STATS for robustness checks.

I obtain financial data from Compustat. I collect firms' diversity and multination information from Four Twenty Seven's facility statistics. I collect firms' disclosed climate risks from CDP to approximate firms' perceived climate risks. Firms disclosed climate risks include magnitude, likelihood, and influencing time of each climate risk driver.

In addition, I collect some qualitative evidence to facilitate the interpretation of the empirical results. First, I interview 12 sustainability directors/consultants in the U.S. and Asia. Second, I review CDP reports, sustainability reports, and annual financial reports of over 1,500

[16] Few countries have adaptation regulations in place. Some countries started to require public companies to disclose climate risk information in recent years. For instance, in 2016, Article 173 of the French Energy Transition Law mandated that publicly traded firms report their physical and transition climate risks (UNPRI 2016). The U.S. Federal Reserve included climate change in a list of key risks to the US financial stability in November 2020 (Ceres 2020).

[17] In addition, although I cannot validate all firms' disclosed adaptation measures with their actual practices, I find firms' disclosed climate risks in CDP reports are positively associated with the modeled climate risk scores, as reported in Table 4. It suggests that firms' disclosed climate risk information is in line with that predicted by climate science. It also implies that firms' disclosed adaptation strategies are likely to align with their actual ones.

firms between 2010 and 2019, which provide textual information on firm adaptation to climate risk. Online Appendix C provides more detailed information on the qualitative evidence.

Data Merging

I merge firms' adaptation data with ESG and financial data at the firm-year level. I perform the firm-level matching using ISIN as the primary identifier. I merge the adaptation data with climate risk data at the firm-climate risk level, as illustrated in Figure B.2 of Appendix B. For matching at the climate risk level, I manually adjust the climate risk names in the CDP data based on textual descriptions of these risks to match with the names and definitions of climate risk drivers in the Four Twenty Seven data. The final sample covers adaptation strategies of 1,068 public companies headquartered in 43 countries in response to five climate risk drivers between 2011 and 2017.[18]

Definition of Variables

Table 1 provides definitions and summary statistics of different variables. Panel A provides the description, while Panel B presents the correlation between variables.

******* Insert Table 1 Here**********

Outcome Variables

I use *adapt dummy* to measure whether a firm initiates adaptation strategies. It is a dummy variable equal to 1 if a company has one or more adaptation strategies to a climate risk driver and equals to 0 if not. I use *adapt breadth* to capture the scope of firms' adaptation strategies and the extent to which firms adapt by pursuing different strategies simultaneously. I construct *adapt breadth* by counting the number of adaptation strategies firms take across categories in response to each

[18] To assess whether the companies disclosing climate information through CDP are representative of the broader universe of public firms, I focus on S&P500 companies and compare firms with and without CDP climate risk disclosure. As is shown in Table H.1 in Appendix H, the two groups of firms are similar in most aspects such as climate risk scores and financial performance. The sizes of companies disclosing climate risk information through CDP are larger. To assess whether companies in the merged sample are representative of all companies disclosing climate information through CDP, I consider all companies disclosing data through CDP and compare firms with and without climate risk scores. As shown in Table G.2 in Appendix G, the two groups of firms are similar in most aspects such financial performance and ESG performance. The only significant difference is that firms in the sample have larger size. While the size difference does not bias the estimates within the estimation sample, they can potentially restrict the external validity of the findings. Whether the results of the study generalize to smaller companies is an important avenue for future research.

climate risk driver. [19]

To explore different directions of adaptation strategies, I also decompose firms' adaptation strategies into two types: *operational strategies* and *business strategies*. Operational strategies are actions that allow firms to maintain business as usual, such as risk assessment, risk management, and risk transfer. Business strategies are actions corresponding to strategic changes such as technology adoption, market diversification, relocation, and innovation. Compared to operational strategies, business strategies are associated with firms' core business, such as capital expenditure, land, innovation, and workforce. The categories and examples of these two types are detailed in Table B.1 of Appendix B. Therefore, there are three measurements for *adapt dummy*: 1) *adapt strategy dummy*; 2) *operational strategy dummy, and* 3) *business strategy dummy;* and three measurements for *adapt breadth:* 1) *adapt strategy breadth*; 2) *operational strategy breadth*; and 3) *business strategy breadth.*

Explanatory Variables

I measure the level of *climate risk* by using Four Twenty Seven's climate risk scores at the firm-climate risk level, which range from 0 to 100. A higher climate risk score indicates higher climate change exposure.

To measure firms' *ESG* performance, I consider four main categories classified by MSCI: environment, community, diversity, and corporate governance. The community and diversity categories are combined to measure social performance, and thus I have three major categories: environmental, social, and corporate governance. I count the number of strengths within each category and construct the score for each category in each year. The overall ESG score is the sum of the strengths of all three categories. A higher ESG score indicates a better ESG performance.

In addition to strengths, the MSCI database also contains a list of ESG concerns. In the robustness checks, I count the number of strengths and concerns within each of the categories and subtract the number of concerns from the number of strengths to construct the "net" score for each

[19] Other studies have used similar constructs (e.g., Hoffmann et al., 2009; Slawinski and Bansal, 2015).

category in each year (following Servaes and Tamayo (2013) and Cao et al. (2019)). The alternative ESG score is the sum of the net scores of the three categories.[20]

Control Variables

I construct firms' financial control variables based on data from Compustat. *Size* is the natural logarithm of the book value of total assets. *Return on Assets* (ROA) is the ratio of operating income before depreciation to the book value of total assets. *Leverage* is the ratio of debt (long-term debt plus short-term debt) to the book value of total assets. *Cash* holding is the ratio of cash and short-term investments to the book value of total assets. *FirmAge* is the year in the analysis minus the year a firm was founded.

I calculated other firm-level control variables based on facility statistics from Four Twenty Seven. *Diversity* is the number of SIC divisions a firm's facilities cover. *Multination* is a dummy variable and equals one if a firm has operations in countries outside its headquarters.

METHODOLOGY

To assess firm adaptation in response to different climate risk levels, I estimate the following model in the baseline:

$$Adapt_{irt} = \alpha_i + \alpha_r + \alpha_t + \beta ClimateRisk_{ir} + \gamma' X_{it-1} + \varepsilon_{irt} \quad (1)$$

The unit of analysis is firm-climate risk-year. The firm-climate risk level analysis is important. It enables me to not only examine firms' adaptation strategies across firms, but also to identify how firms adapt to different climate risk drivers. Firms are indexed by *i*, risks are indexed by r, and years are indexed by *t*. $Adapt_{irt}$ is a generic term standing for respectively *adaptation strategy dummy, operational strategies dummy, business strategies dummy, adaptation strategy breadth, operational strategies breadth,* and *business strategies breadth.* $ClimateRisk_{ir}$ measures the climate risk level of company *i* for climate risk driver *r*. Note that climate risk varies across firms and risks,

[20] I don't use the "net" score in the baseline because some studies suggest that MSCI strengths and concerns lack convergent validity—using them in conjunction doesn't provide a valid measure of ESG (Mattingly & Berman 2006). Nevertheless, in robustness checks I show that using the net index I obtain similar results.

but not across years. The regression includes fixed effects for each firm α_i , climate risk α_r , and year α_t, as well as a vector of control variables *X*, including size, ROA, leverage, and cash holdings. The residual is denoted by ε_{irt}. Standard errors are clustered at the firm level.

The regression in equation (1) is estimated by ordinary least squares (OLS). The OLS baseline regression with firm fixed effects and climate risk driver fixed effects identifies within-firm between-risk variation and examines how firms adapt to different climate risk drivers. The coefficient of interest is β, which measures the association between climate risks and the likelihood or scope of a firm's adaptation strategies. If β is positive and statistically significant, it suggests that firms are more likely to adapt or adopt a broader range of adaptation strategies to address specific climate risk drivers with higher climate risk scores.

The inclusion of firm fixed effects accounts for unobserved heterogeneity of the firm characteristics. The inclusion of climate risk fixed effects accounts for the heterogeneity of different climate risk drivers (e.g., if it is more costly to adapt to certain types of risks, we might see less responsiveness for that category). The inclusion of control variables mitigates the possibility that the findings are driven by some firm-year level omitted variables. For example, it could be that larger companies or companies with more cash holdings have more resources to adapt to climate change. Also, larger firms may be under more intense public scrutiny, which may lead to more strategic action. Controlling for firm size and cash holdings addresses this potential confounding influence. Similarly, the other controls account for differences in performance (ROA and market-to-book), financing policies (leverage and cash holdings), and firm operations (diversity and multinational operations) that may correlate with the decision to adapt. To facilitate interpretation, I standardize all variables.

If we assume that climate risks are exogenous, then equation (1) estimates a causal impact of physical climate risk on firm's adaptation strategies. Although this assumption seems reasonable, one might be concerned that unobserved variables could lead to spurious correlation. For instance, geographic sorting of people with different attitudes towards climate might lead to a correlation between physical climate risk and firm strategies, even if the mechanism is not a direct response to climate risk *per se*, but rather a correlation between the climate in a particular location and the attitude of the managers who live there. Concerns of this type should largely be addressed, however, by including firm fixed effects that will capture any overall tendency of a firm towards adaptation. In particular, in models with firm effects, the coefficient β measures a firm's responsiveness to the specific risks that are highest according to Four Twenty Seven. Also, to the extent that firms have rarely considered future climate risks when investing in new facilities or undertaking M&A or spin-off actions in practice, it seems reasonable to assume that the distribution of climate risk faced by a particular firm is exogenous.[21]

To test whether firms are more likely to adapt when they have better ESG performance, I estimate a model that allows the impact of *climate risk* to vary by firms' *ESG* performance. Specifically, I estimate the following regressions:

$$Adapt_{irt} = \alpha_r + \alpha_{jct} + \beta 1 ClimateRisk_{ir} + \beta 2 ESG_{it-1} + \delta ClimateRisk_{ir} * ESG_{it-1} + \gamma' X_{it-1} + \varepsilon_{irt} \quad (2)$$

In this specification, β_1 measures the association between *climate risk* and adaptation with the sample average ESG, β_2 measures the association between ESG and adaptation with the sample average climate risk, and δ indicates whether the impact of ESG performance varies with different climate risk levels. To explore whether different ESG components drive the influence, I also decompose ESG into environmental (E), social (S), and corporate governance (G), and run the regression separately.

RESULTS

Descriptive Analysis

[21] Between 2010 and 2019, the CDP reports that less than 1 percent of firms relocated their headquarters or facilities in response to climate risks each year. This concern is also mitigated by the climate risk scores collected from Four Twenty Seven, which estimate firms' climate change exposure at the end of the sample period.

Figure 1 presents firms' average probability of adaptation by climate risk drivers. *Adaptation dummy* indicates the percentage of firms' disclosed adaptation to different types of climate risks, regardless of climate risk levels. *Adaptation dummy* is decomposed into *operational strategies dummy* and *business strategies dummy*. Figure 1 suggests a few interesting findings. First, most firms do not adapt to most climate risk drivers. The average adaptation rates across firms and climate risk drivers are 23%. Among various climate risks, the percentage of firm adaptation is highest for floods, but it is still less than 30%. The qualitative evidence I collect supports those arguments and provides additional explanations for the low adaptation rates. Because of the uncertainties inherent in differing climate change models, decision-makers may have different views on the potential impacts when they assess climate information. For instance, one U.S. retail company stated that "due to the lack of consensus on the magnitude and likelihood of sea-level rise, the company is challenged to develop a strategy to reduce this particular risk."[22] Also, some companies focus on climate change mitigation, not adaptation. One natural resource company in Canada disclosed that their "climate risks are primarily concerned with policy and regulation changes, not with changes in physical climate parameters."[23]

Second, firms adapt more through operational than business strategies. A plausible explanation for this finding is that operational strategies are relatively quick to initiate or less costly than business strategies. They can be easily justified even if there is no climate change. For instance, one financial firm in Japan developed a business continuity plan not only for climate risks but also "for a major earthquake or the potential outbreak of a new strain of influenza."[24] In contrast, shifting business strategies is more difficult. For example, one U.S. financial company targeting low-income communities said in an interview that they could not easily withdraw from their existing customers, even though their climate change vulnerability is high.[25]

[22] Disclosure in CDP report. Accessed in August 2020.
[23] Disclosure in CDP report. Accessed in September 2020.
[24] Disclosure in CDP report. Accessed in August 2020.
[25] Interview conducted on 21 May 2020.

Third, the different adaptation rates between operational and business strategies are salient for acute climate risks such as floods and hurricanes/typhoons, but not for chronic climate risks such as water and heat stresses. One possible explanation is that chronic climate risks bring gradual shifts in climate parameters and provide time for firms to prepare and respond to gradual impacts. Thus, firms might be more likely to adapt through business strategies.

******* Insert Figure 1 Here**********

Figure 2 plots climate risk scores and the probability of adaption across industries. Overall, industries with higher climate risk are more likely to adapt. Appendix D provides more detailed climate risk and adaptation information by industry and climate risk driver. On average, real estate has the highest overall climate risk. The utility industry has the highest heat stress risk; the energy industry has the highest water stress risk; real estate has the highest sea level rise risk; and the hardware technology industry has the highest flood and hurricane/typhoon risk. This makes sense, as resource-intensive sectors are more directly affected by extreme heat and water scarcity.

******* Insert Figure 2 Here**********

Figure 3 shows the evolution of adaptation strategies over time. Firm adaptation increases over the sample period, particularly for adaptations that I categorize as business strategies. While only about 7% of firms disclose their adaptations through business strategies in 2011, the percentage rises to 13% in 2017. However, although business strategies increase faster than risk management over time, firms still adapt more through operational strategies than business strategies on average. This suggests that firms take time to perceive, assess, and respond to higher climate risks. Firms' perceptions of climate risk may evolve as new information is revealed over time via climate-related weather events, news reporting of climate events, and the publication of climate science studies. In addition, as operational strategies typically require fewer resources and are relatively quick to initiate, firms may adopt them at an early stage. Business strategies, in contrast, need more time, and firms may adopt them gradually at a later stage. As such, it is not surprising that the adoption of business strategies grows over time, compared to operational strategies.

******* Insert Figure 3 Here**********

Online Appendix D presents additional descriptive statistics. Table D.2 reports the *adaptation breadth* data, which indicates the scale of different adaptation categories and suggests similar results as that of the *adaptation dummy*.

Climate Risks and Adaptation Strategies

To test H1 and examine whether firms facing higher climate risks are more likely to adapt, and how, I estimate the baseline specification. Table 2 presents the results. Model 1 uses pooled cross-sectional regression with country-year-industry and climate risk fixed effects and estimates the impact of higher levels of climate risks on firms' adaptation strategies across firms and climate risk drivers. Model 2 uses Equation 1 with firm, year, and climate risk fixed effects and estimates the impact within firm and between climate risk drivers. Overall, the results in Table 2 indicate that higher climate risk increases firm adaptation, including the likelihood and adaptation breadth. The results are statistically significant across firms and within-firm between climate risk drivers.

******* Insert Table 2 Here**********

Specifically, results of Model 1 suggest that when facing higher climate risks, firms are more likely to adapt. Increased adaptation comes through both operational and business strategies, and increases the overall scope of adaptation strategies. Results of Model 2 suggest that firms are more likely to adapt and with a broader scope of strategies in response to higher climate risks within firm and between climate risk drivers. The statistically significant and positive coefficients on *climate risk* in Model 2 suggest that one standard deviation increase of *climate risk* increases a 6.2% standard deviation of *adaptation breadth* (with p-values < 0.01). One standard deviation increase of *climate risk* increases 6.1% standard deviation of *operational strategies breadth* and 3.8% standard deviation of *business strategies breadth*. Climate risks include a broad scope of risks. As adaptation strategies require firm resources and compete with other firms' operational and strategic objectives, firms may be more likely to adapt to some climate risk drivers that are expected to have greater impacts on the firm, instead of adapting to all climate risk drivers. They are also more likely to adopt broader scope of adaptation strategies in response to those specific climate risk drivers.

In Appendix E, I provide several robustness checks for the baseline analysis. The results are robust 1) when I use the logit model when the outcomes *adaption dummy* (Table E.1); 2) when I use alternative models with different fixed effects (Table E.2); 3) when I use other control variables (Table E.3); 4) when I ran cross-sectional analyses for Model 1 in the year 2011 and 2017 (Table E.4); 5) when I use log form for *climate risk* (Table E.5), and 6) when I combine the outcome and explanatory variables at the firm level (Table E.6).[26]

ESG and Firms' Adaptation to Climate Risk

To test H2 and examine whether firms with better ESG performance are more likely to adapt to higher climate risks, I estimate the specification in Equation 2. The results are presented in Table 3. Consistent with the results in Table 2, higher climate risk is associated with more adaptation. The coefficient on *climate risk*, which measures the impact of climate risk with the sample average ESG, indicates around a 6.9% percent standard deviation increase in *adaptation breadth (Model 2)*. However, firms with better ESG performance do not necessarily have more adaptation on average. The coefficients on *ESG,* which measure the association between ESG and adaptation with the sample average climate risk, are positive but not statistically significant. More interestingly, firms with higher ESG ratings are more likely to adapt and have a broader scope of adaptation when facing higher climate risks. The positive and statistically significant coefficient on the interaction term between *climate risk* and *ESG* (p-value<0.01) indicates that one standard deviation increase in ESG performance increases this elasticity by 41% (0.028/0.069=0.41). The results are consistent with the H2 prediction.

******* Insert Table 3 Here**********

[26] As suggested in Table E.6 in Appendix E, a higher level of firms' aggregate climate risk increases the breadth of firms' overall adaptation strategies. The results are statistically significant for *adaptation breadth* and *operational strategies breadth,* but not for *business strategies breadth*. It is plausible that when combining different climate risks and adaptation measures at the firm level the measurement becomes noisy.

As discussed in the Framework section, the positive interaction admits at least two different interpretations. One possibility is that better ESG performance is associated with firms' higher perceptions of climate risk. A second possibility is that ESG strengths proxy for firms' climate change adaptive capabilities because the resources obtained by firms to increase their ESG performance have synergies with climate change adaptation and prepare them to adapt when facing higher climate risk. The following section will further disentangle the two potential channels.

In Appendix F, I provide several robustness checks for the above analysis. The results are robust 1) when I use the ESG score in 2011[27] only instead of the time-varying ESG data (Table F.5); 2) when I use "net" ESG scores, i.e., subtracting ESG controversies count from ESG strengths count (Table F.6), instead of ESG strengths; 3) when I use ESG scores from different rating agencies such as ASSET4 and Sustainalytics (Tables F.7 and F.8).

Mechanisms: Climate Risk Perception and Adaptive Capability

In this section, I explore the potential mechanisms for H1 and H2 and examine 1) whether higher climate risks increase firms' climate risk perception; and 2) whether the influence of ESG on firms' adaptation to higher climate risk is through firms' increased climate risk perceptions or their superior adaptive capability.

As firms' climate risk perception is unobservable, I use firms' disclosed climate risk to approximate their risk perceptions. Every year firms disclose the impacts of different climate risks in their CDP reports. The disclosed climate impacts include the *magnitude*, *likelihood*, and *influencing time* of different climate risk drivers. I code different levels of disclosed climate risk impacts by using different scores (see coding details in Panel A of Table 1). Higher scores indicate greater magnitude, greater likelihood, and shorter-term influencing time of climate risks. I replace the outcome variable in equation (2) with firms' disclosed climate impacts. Because these outcomes

[27] I didn't use the ESG data in 2010 because KLD was acquired by MSCI in 2010.

reflect firms' climate risk perceptions, a positive correlation between the modeled climate risk and disclosed climate impacts is consistent with the presence of the climate risk perception channel.

******* Insert Table 4 Here**********

The results are reported in Table 4. The results suggest that higher levels of climate risks increase firms' climate risk perception. The statistically significant coefficients on *climate risk* indicate that firms' climate risk perceptions, measured by disclosed climate impacts in terms of *magnitude*, *likelihood*, and *influencing time,* are positively associated with firms' modeled *climate risks*. The increased climate risk perception triggers managers to re-evaluate the up-and down-sides of adaptation and induces them to adapt.

Counterintuitively, I don't find an association between firms' ESG performance and higher climate risk perception. The coefficients on the interaction term between *climate risk* and *ESG* are not significantly different from zero. Combing Tables 3 and 4, the results suggest that although firms with better ESG performance are more likely to adapt when facing higher climate risks, it is *not* because high ESG performing firms perceive higher climate risks differently. As the results reject the first channel discussed in the Framework, they imply that the influence of ESG on firms' adaptation is likely through the second channel, i.e., firms' climate change adaptive capability. It is likely that firms with better ESG are more likely to obtain capabilities that enable them not only to manage their environmental and social impacts well, but also to adapt better when facing and perceiving higher climate risks.

Auxiliary Analysis

Change Over Time

Given that climate change has become a significant issue for stakeholders only recently, I explore how firms' adaptation to the level of climate risks has changed over time. As modeled in other papers (Dowell, Lyon and Pickens 2020; Doshi, Dowell, and Toffel 2013), I use *Trend* = Year – 2010, and interact it with the *ClimateRisk* to identify the difference in trends between adaptation strategies and climate risk levels. The results are presented in Table 5. The coefficients on *climate* *risk* measures the impact of climate risk level on the firms' adaptation strategies over time at the firm-climate risk level. As suggested in Table 5, the coefficients are positive and statistically significant for regressions on *adaptation* and *business strategies* (p-values < 0.01) (including dummy as well as breadth). The coefficients on *climate risk* for regression on *operational strategies*, however, are not significantly different from zero. The results suggest that over time, firms adapt more and with a broader scope of adaptation strategies to higher climate risks, particularly for business strategies. The likelihood and the scope of operational strategies don't significantly increase over time in response to higher climate risks.

******* Insert Table 5 Here**********

As operational strategies are relatively quick to initiate, it is plausible that firms adopt operational strategies in response to higher climate risks at an early stage. Over time, however, higher climate risks may require different organizational responses such as business strategies and are likely to exceed thresholds for operational ones. For instance, in recent years Landsec disclosed that it avoided acquisition of properties with proximity to the coast, and dated coastal defenses, as the sea-level rise is expected to impact the coastal regions of the UK and could increase the storm surge flooding. In 2020, Ecolab spun off its upstream energy business, which is exposed to physical climate risks of Gulf Coast suppliers.

<u>Decomposing ESG into E, S, and G</u>

To explore whether the influence of ESG on firms' adaptation to climate risk is driven by environmental, social, or corporate governance performance, I replace ESG strengths with environmental (E), social (S), and corporate governance (G) strengths in Equation (2) and conduct similar regression analyses separately, as summarized in Tables F.1 to F.3 in Appendix F. I also replace ESG strengths with combined environmental and social strengths and run a similar analysis, as presented in Table F.4. The results suggest that the ESG influence on firms' adaptation to higher climate risk is mainly driven by firms' environmental and social performance, not corporate governance. The results imply that firms' environmental and social impact management and their adaptation to the impact of the environment can be connected and complemented.

Heterogeneity Among Different Regions

In addition, I explore the regional heterogeneities and examine whether the results vary according to the location of firms' headquarters. I re-estimate the baseline specification for four regions: *Asia, Europe, North America*, and *Other Regions,*[28] and Figure 4 graphically displays the *climate risk* coefficients. I also ran regressions to compare differences among regions, and the results are summarized in Table G.1 in Appendix G. The results indicate that firms headquartered in Europe and North America are more likely to adapt when facing higher climate risks. However, in Asia and other regions, the estimated coefficients on climate risk are not significantly different from 0, indicating that firms headquartered in Asia and other regions are not more likely to adapt in response to higher climate risks.

******* Insert Figure 4 Here**********

To explore some potential explanations for the heterogeneous responses among regions, I examine the moderating effects of some institutional factors in Appendix G. As presented in Table G.2, firms are more likely to adapt through *business strategies* when facing higher climate risks, and this relationship is especially pronounced for firms headquartered in countries with higher Climate Change Performance Index, which indicates higher climate change awareness. Also, firms headquartered in countries with greater *insurance penetration*, which indicates higher risk management awareness, are more likely to adapt through *operational strategies* when facing higher climate risks. I don't find economic factors, such as country-level GDP per capita, influence firms' adaptation to climate risks (Table G.3). A country's globalization level influences firms' adaptation breadth, but not the likelihood of adaptation to climate risks (Table G.4). These results provide some plausible explanations for the regional heterogeneities. Countries in Asia may have lower average climate change and risk management awareness. Thus, companies headquartered in these regions are not more likely to adapt even if they face higher climate risks.

[28] I combine all other countries because the sample size for companies headquartered in countries outside North America, Europe, and Asia is small.

CONCLUSION

Do companies adapt to the increased climate risks they are facing? If so, how and under what conditions? While a large literature has focused on how firms *mitigate* their contributions to global climate change, surprisingly we know little about how firms *adapt* to physical climate risks. By developing a novel dataset on firms' disclosed adaptation strategies and merging it with climate science data, this study systematically examines whether, how, and under which conditions firms adapt to climate risks.

I find that most firms don't adapt to most climate risk drivers. However, firms are more likely to adapt through both operational and business strategies in response to the specific risk factors most salient to their own business. Moreover, the positive impact of climate risks on firms' adaptation strategies increases over time, particularly for business strategies. I explore the mechanism underlying firms' adaptation strategies and identify firms' climate risk perception as critical for increased firm adaptation. I also find that firms with better environmental and social performance ratings are more responsive to higher climate risks in adaptation, which is likely driven by their better capabilities to adapt. There are heterogeneities across regions, and I find firms headquartered in regions outside Europe and North America are not more likely to adapt when facing higher climate risks.

The study makes several contributions. First, it contributes to the literature on organization adaptation to environmental changes (for a review, see Sarta, Durand and Vergne 2021). While previous studies focus on short-term or cyclical changes (Aghion et al 2012; Anand and Singh 1997; Fabrizio and Tsolmon 2014; Flammer and Ioannou 2021), little is known about firm strategies when facing long-term, systemic, and irreversible crisis such as climate change, which is the focus of this study. This study explores this substantially different type of external change by examining how firm adaptation to physical climate change. It is exploratory in nature. I follow Hambrick's (2007) and Helfat's (2007) recommendations and document the critical phenomena in the hope that it will stimulate future theoretical and empirical works in this area.

Second, this study focuses on firms' adaptation instead of mitigation strategies in response to climate change and advances our understanding of firms' relationship with the environment. It builds on previous work that has conducted case studies (Canevari-Luzardo et al. 2019; Hamann et al. 2020; Linnenluecke, Stathakis, Griffiths 2012) and proposed conceptual frameworks (Berkhout 2012; Clement and Rivera 2017; Linnenluecke and Griffiths 2010; Winn et al. 2011). While previous studies usually focus on one single climate risk driver in one specific sector (Hoffmann et al. 2009; Galbreath 2014; Busch 2011; Gasbarro et al. 2014), I explore firms' adaptation to different climate risk drivers across industries and countries, and find that firms are more likely to adapt to climate risks with higher exposures, although there are heterogeneities across firms and countries.

Third, this study contributes to the extant literature by examining how non-market strategies such as ESG can interact with firms' market strategies such as adaptation. While previous studies have either focused on the impact of the ESG on firms' competitiveness (e.g., McWilliams and Siegel 2001; Choi and Wang 2009; Flammer 2015; Hawn and Ioannou 2016), or on firms' market strategies in response to business, political, and financial risks (Bloom and Milkovich 1998; Delios and Henisz 2000; Oh and Oetzel 2011), they are usually examined separately. In this study, I examine how firms' ESG performance and adaptation strategies can be connected and complemented.

Finally, this paper contributes to the sustainability literature by measuring firms' climate risks and adaptation strategies. I use the novel data from Four Twenty Seven which forecasts firms' climate risk levels based on locations of firms' facilities and climate modeling. Some previous work used historical weather to proxy for the effects of climate change, which may or may not be a good measurement for the impact of future climate change exposure (Dell, Olken, and Jones 2014; Hsiang 2016; Li and Gallagher 2022). Also, I develop adaptation data by hand-coding textual information of the firms' disclosed adaptation. To the best of my knowledge, it is the first longitudinal database on firms' adaptation strategies to different climate risk drivers.

My findings also have both policy and managerial implications. Understanding whether and how firms adapt to climate risks can help regulators decide whether policies on adaptation are needed and which aspects. As most adaptation is not only influenced by the level of climate risks but also by firms' risk perception and their capabilities to adapt, policies and guidelines might be needed to stimulate firms' adaptation. The comprehensive discussion on different climate risk drivers, firms' adaptation strategies, and their interactions with their ESG can be informative to managers. The results are also informative to investors as adaptation can reduce firms' climate risks and thus potentially increases returns in the long run.

This study has limitations and opens several avenues for future research. First, the outcome variable in the study is measured by disclosed adaptation strategies, which is the best possible measurement I can obtain at this stage. Future research could select a small group of adaptation strategies (e.g., innovation or location choice) and collect data on whether firms actually implement specific adaptation strategies. Second, there are inherent uncertainties in climate risk data predicted by climate models. Still, for now, they are the best data available to measure firms' future climate change risk, instead of historical weather patterns. Third, this study focuses only on the climate risks of large public firms' direct operation. It would be interesting for future research to explore the impact of climate risks on 1) private firms and other smaller organizations, and 2) firms' different value chains on top of direct operations, such as suppliers and customers.

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Table 1: Summary Statistics

i indexes firms, r indexes climate risk driver, t indexes year, c indexes country.
N = 25,535 firm-risk-year (i,r,t) observations pertaining to 1,068 firms (i) headquartered in 43 countries (c) between 2011 and 2017.
N = 5,107 firm-risk (i,r) observations. N= 301 country-year (c,t) observations.
All variables are standardized to a mean of 0 and a standard deviation of 1 in regression analysis for straightforward interpretation.

Panel A: Description

Variable	Mean	Std. Dev.	Min	Max	Unit of Obs	Note
Outcome Variables						
AdaptStrategyBreadth	0.49	1.04	0.00	11.00	i,r,t	AdaptStrategyBreadth is constructed by adding up adaptation categories the firms have taken in response to one particular climate risk driver.
OpStrategyBreadth	0.31	0.71	0.00	4.00	i,r,t	AdaptStrategyBreadth is decomposed into Operational Strategy Breadth (OpStrategyBreadth) and Business Strategy Breadth (BuStrategyBreadth).
BuStrategyBreadth	0.17	0.56	0.00	8.00	i,r,t	AdaptStrategyBreadth is decomposed into Operational Strategy Breadth (OpStrategyBreadth) and Business Strategy Breadth (BuStrategyBreadth).
AdaptStrategyDummy	0.23	0.42	0.00	1.00	i,r,t	AdaptDummy is a dummy equals to 1 if a firm adapt to one climate risk driver in any adaptation category.
OpStrategyDummy	0.19	0.40	0.00	1.00	i,r,t	AdaptDummy is decomposed into Operational Strategy Dummy (OpStrategyDummy) and Business Strategy Dummy (BuStrategyDummy).
BuStrategyDummy	0.11	0.32	0.00	1.00	i,r,t	AdaptDummy is decomposed into Operational Strategy Dummy (OpStrategyDummy) and Business Strategy Dummy (BuStrategyDummy).
DisclosedLikelihood	1.62	2.64	0.00	8.00	i,r,t	1-"Exceptionally unlikely"; 2 - "Very unlikely" ; 3 "Unlikely"; 4 - "About as likely as not"; 5- "More likely than not"; 6-" Likely"; 7-" Very likely"; 8-" Virtually certain"
DisclosedImpact	0.86	1.51	0.00	5.00	i,r,t	1 -" Low" ; 2 - "Low-medium"; 3 - "Medium"; 4 - " Medium-high"; 5 -"High"
DisclosedInfluencingTime	0.67	1.31	0.00	4.00	i,r,t	1- Long term; 2- Medium term; 3-Short term; 4-Current
Explanatory Variables						
ClimateRisk	28.13	17.10	0.00	100.00	i,r	ClimateRisk is the average climate risk score of different risk types for a given firm's direct operation.
HeatStress	39.62	12.14	2.98	93.1	i,r	One of the five climate risk drivers analyzed in the study.
WaterStress	42.89	12.56	0	89.98	i,r	One of the five climate risk drivers analyzed in the study.
SeaLevelRise	12.66	11.44	0	80	i,r	One of the five climate risk drivers analyzed in the study.
Floods	25.05	12.18	0	89.82	i,r	One of the five climate risk drivers analyzed in the study.
Hurricans/Typhoons	29.87	25.24	0.00	100.00	i,r	One of the five climate risk drivers analyzed in the study.
Moderators						
ESG Strength	1.29	2.08	0.00	12.00	i,r	ESG strength - firms' overall environmental, social, and corporate governance strengths counts in a given year.
CCPI	52.92	8.62	35.57	77.76	c,t	CCPI is the Climate Change Performance Index for each country in a given year.
InsurancePenetration	3.37	1.14	0.46	7.67	c,t	InsurancePenetration is the country level non-life insurance penetration rate.
Control Variables						
Size	10.11	1.56	0.00	15.08	i,t	Size is the natural logarithm of the book value of total assets.
ROA	0.12	0.08	-0.54	0.70	i,t	Return on Assets (ROA) is the ratio of operating income before depreciation to the book value of total assets.
Cash	0.12	0.11	0.00	0.89	i,t	Leverage is the ratio of debt (long-term debt plus short-term debt) to the book value of total assets.
Leverage	0.25	0.15	0.00	1.17	i,t	Cash holding is the ratio of cash and short-term investments to the book value of total assets.
FirmAge	73.28	53.82	0.00	358.00	i,t	FirmAge is the Year in the analysis minus the year a firm was founded.
Diversity	6.06	2.19	1.00	11.00	i	Diversity is the number of SIC divisions a firm's facilities cover.
Multination	0.94	0.25	0.00	1.00	i	Multination is a dummy variable and equals to 1 if a firm has operations in countries outside of its headquarters.

Panel B: Correlation

	Adapt Strategy Breadth	OpStrategyBreadth	BuStrategy Breadth	Adapt Strategy Dummy	OpStrategy Dummy	BuStrategy Dummy	Disclosed Likelihood	Disclosed Impact	Disclosed Influencing Time	Climate Risk	ESG Strength	CCPI	Insurance Penetration	Size	ROA	Cash	Leverage	Firm Age	Diversity	Multinational
AdaptStrategyBreadth	1.000																			
OpStrategyBreadth	0.851	1.000																		
BuStrategyBreadth	0.761	0.306	1.000																	
AdaptStrategyDummy	0.853	0.800	0.557	1.000																
OpStrategyDummy	0.801	0.897	0.344	0.892	1.000															
BuStrategyDummy	0.726	0.360	0.869	0.641	0.416	1.000														
DisclosedLikelihood	0.665	0.615	0.444	0.785	0.687	0.510	1.000													
DisclosedImpact	0.608	0.578	0.388	0.727	0.648	0.449	0.825	1.000												
DisclosedInfluencingTime	0.587	0.567	0.363	0.684	0.620	0.421	0.787	0.691	1.000											
ClimateRisk	0.091	0.039	0.117	0.091	0.050	0.114	0.114	0.116	0.104	1.000										
ESG Strength	-0.005	-0.008	0.002	-0.025	-0.025	0.000	-0.064	-0.087	-0.054	-0.017	1.000									
CCPI	0.020	0.031	-0.002	0.001	0.019	-0.016	-0.003	-0.029	-0.014	-0.140	-0.133	1.000								
InsurancePenetration	-0.032	-0.035	-0.016	-0.052	-0.050	-0.018	-0.062	-0.068	-0.043	-0.040	0.292	-0.318	1.000							
Size	0.088	0.088	0.051	0.071	0.080	0.038	0.038	0.007	0.050	-0.076	0.156	0.171	-0.002	1.000						
ROA	0.011	0.001	0.018	-0.004	-0.006	0.019	-0.019	-0.040	-0.013	-0.019	0.127	0.039	0.041	-0.319	1.000					
Cash	-0.051	-0.055	-0.024	-0.051	-0.057	-0.020	-0.046	-0.045	-0.042	0.019	0.003	-0.012	-0.037	-0.197	0.170	1.000				
Leverage	0.062	0.054	0.045	0.060	0.056	0.039	0.065	0.072	0.051	0.010	0.032	0.016	0.010	0.087	-0.119	-0.291	1.000			
FirmAge	0.003	0.010	-0.006	-0.002	0.003	-0.013	-0.011	-0.026	-0.016	-0.011	0.153	0.050	-0.005	0.164	-0.046	-0.124	0.017	1.000		
Diversity	0.040	0.039	0.025	0.031	0.032	0.017	0.013	-0.004	0.014	-0.033	0.125	0.274	-0.141	0.290	-0.013	-0.170	0.127	0.240	1.000	
Multinational	-0.003	-0.002	-0.004	-0.005	-0.003	0.009	-0.003	0.004	0.028	-0.004	0.015	0.082	-0.035	0.078	0.030	0.144	-0.004	0.070	0.250	1.000

Table 2: Physical Climate Risks and Firms' Adaptation Strategies: Full Sample

Unit of analysis is Firm-Risk-Year. The sample period is 2011 - 2017.
Outcome variable is Climate Change adaptation. Adaptation indicates adaptation strategies, which are also decomposed into operational and business strategies. The main explanatory variable *ClimateRisk* is the climate risk score. All regressions include Climate Risk Driver fixed effects. Model 1 has Country-Industry-Year fixed effects. Model 2 includes firm fixed effects and year fixed effects. Robust standard errors clustered at the firm level are in parentheses. All variables are standardized to a mean of 0 and a standard deviation of 1 for easy interpretation.
* p<0.10, ** p<0.05, *** p<0.01

	Model 1 - Pooled Cross Section				Model 2- Firm Fixed Effects			
	Adaptation Dummy	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Dummy	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.068	0.068	0.066	0.042	0.067	0.062	0.061	0.038
	[0.018]	[0.016]	[0.016]	[0.016]	[0.017]	[0.016]	[0.016]	[0.016]
Controls								
Size	0.131	0.142	0.129	0.098	-0.051	-0.025	0.044	-0.103
	[0.030]	[0.034]	[0.032]	[0.028]	[0.042]	[0.072]	[0.058]	[0.078]
Cash	-0.042	-0.043	-0.043	-0.024	-0.001	0.003	0.014	-0.011
	[0.022]	[0.020]	[0.019]	[0.018]	[0.019]	[0.022]	[0.021]	[0.022]
ROA	0.036	0.056	0.031	0.064	-0.011	-0.024	-0.025	-0.013
	[0.027]	[0.035]	[0.032]	[0.028]	[0.019]	[0.020]	[0.018]	[0.021]
Leverage	0.007	0.003	0.004	0.000	0.012	-0.008	-0.011	-0.001
	[0.021]	[0.024]	[0.023]	[0.020]	[0.022]	[0.030]	[0.027]	[0.031]
FirmAge	0.008	0.002	0.009	-0.006				
	[0.021]	[0.022]	[0.022]	[0.018]				
Diversity	0.022	0.02	0.011	0.024				
	[0.025]	[0.026]	[0.025]	[0.024]				
Multination	0.012	0.022	0.006	0.032				
	[0.025]	[0.027]	[0.022]	[0.029]				
Country-Industry-Year	Yes	Yes	Yes	Yes				
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE					Yes	Yes	Yes	Yes
Year FE					Yes	Yes	Yes	Yes
N	24430	24430	24430	24430	24450	24450	24450	24450
R2	0.177	0.186	0.175	0.174	0.033	0.029	0.027	0.036

Table 3: ESG and Firms' Adaptation to Physical Climate Risk

Unit of analysis is Firm-Risk-Year. The sample period is 2011 - 2017.
Outcome variable is Climate Change adaptation. Adaptation indicates adaptation strategies, which are also decomposed into operational and business strategies. The main explanatory variables are *ClimateRisk* and ESG scores. All regressions include Climate Risk Driver fixed effects. Model 1 includes Country-Industry-Year fixed effects. Model 2 includes Firm fixed effects and year fixed effects. Robust standard errors clustered at the firm level are in parentheses. All variables are standardized to a mean of 0 and a standard deviation of 1 for easy interpretation. * p<0.10, ** p<0.05, *** p<0.01

	Model 1 - Pooled Cross Section				**Model 2- Firm Fixed Effects**			
	Adaptation Dummy	**Adaptation Breadth**	**Operational Strategies Breadh**	**Business Strategies Breadth**	**Adaptation Dummy**	**Adaptation Breadth**	**Operational Strategies Breadth**	**Business Strategies Breadth**
ClimateRisk	0.075	0.076	0.074	0.046	0.073	0.069	0.068	0.041
	[0.018]	[0.017]	[0.016]	[0.016]	[0.018]	[0.017]	[0.016]	[0.016]
ESGScore	0.018	0.017	0.011	0.018	0.003	-0.010	0.000	-0.018
	[0.025]	[0.032]	[0.028]	[0.030]	[0.013]	[0.015]	[0.016]	[0.015]
ClimateXESG	0.029	0.033	0.026	0.027	0.025	0.028	0.021	0.025
	[0.011]	[0.012]	[0.010]	[0.012]	[0.010]	[0.010]	[0.009]	[0.011]
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry	Yes	Yes	Yes	Yes				
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE					Yes	Yes	Yes	Yes
Year FE					Yes	Yes	Yes	Yes
N	22760	22760	22760	22760	22780	22780	22780	22780
R2	0.182	0.192	0.178	0.18	0.034	0.03	0.029	0.037

Table 4: Physical Climate Risks, ESG, and Firms' Climate Risk Perception

Unit of analysis is Firm-Risk-Year. The sample period is 2011 - 2017.
Outcome variable: Disclosed Climate Risk, including Disclosed Climate Magnitude, Likelihood, and Influencing Time. The greater the magnitude and likelihood of the impact and the shorter the impact are expected to happen, the higher the ratings. The main explanatory variables are climate risk scores and ESG scores.
All variables are standardized to a mean of 0 and a standard deviation of 1 for easy interpretation.
Robust standard errors clustered at the firm level are in parentheses. * p<0.10, ** p<0.05, *** p<0.01

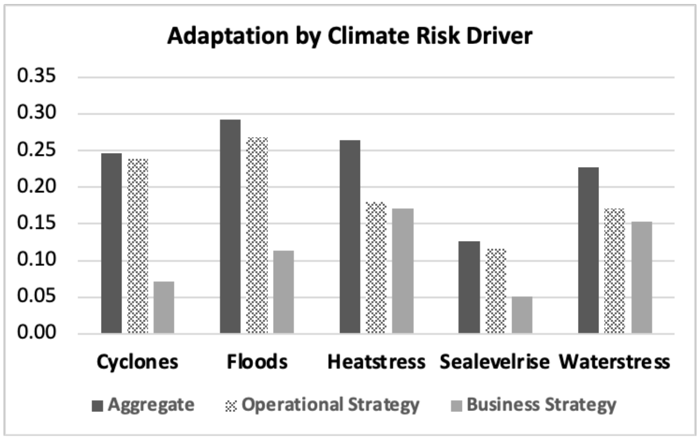
	Model 1			Model 2		
	Disclosed Influencing Time	**Disclosed Likelihood**	**Disclosed Magnitude**	**Disclosed Influencing Time**	**Disclosed Likelihood**	**Disclosed Magnitude**
ClimateRisk	0.049	0.042	0.049	0.043	0.043	0.049
	[0.017]	[0.017]	[0.019]	[0.017]	[0.017]	[0.019]
ESG	0.006	0.014	0.003	-0.008	-0.003	-0.01
	[0.021]	[0.023]	[0.021]	[0.013]	[0.011]	[0.011]
ClimateXESG	0.008	0.004	0.005	0.006	0.000	0.001
	[0.009]	[0.009]	[0.009]	[0.008]	[0.008]	[0.008]
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Year-Industry FE	Yes	Yes	Yes			
Firm FE				Yes	Yes	Yes
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	21261	21359	21369	21334	21431	21440
r2	0.247	0.268	0.251	0.104	0.127	0.097

Table 5: Physical Climate Risks and Firms' Adaptation Strategies: Change Over Time

Unit of analysis is Firm-Risk-Year. The sample period is 2011 - 2017. Outcome variable is Climate Change adaptation. Adaptation indicates adaptation strategies, which are also decomposed into operational and business strategies. Adaptation Breadth is constructed by adding adaptation categories the firms have taken in response to one climate risk driver. Trend = Year - 2010, and it interacts with the treatment of Climate Risk. All regressions include year and firm-risk fixed effects. Robust standard errors clustered at the firm level are in parentheses. All variables are standardized to a mean of 0 and a standard deviation of 1 for easy interpretation. * p<0.10, ** p<0.05, *** p<0.01

	Adaptation Dummy	Operational Strategies Dummy	Business Strategies Dummy	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
TrendXClimateRisk	0.062	0.020	0.089	0.070	0.009	0.117
	[0.020]	[0.021]	[0.021]	[0.021]	[0.021]	[0.023]
Controls						
Size	-0.051	0.012	-0.122	-0.026	0.044	-0.103
	[0.039]	[0.042]	[0.055]	[0.050]	[0.043]	[0.058]
Cash	-0.001	-0.006	-0.009	0.004	0.014	-0.011
	[0.015]	[0.016]	[0.017]	[0.017]	[0.017]	[0.018]
ROA	-0.01	-0.008	-0.013	-0.024	-0.025	-0.013
	[0.015]	[0.015]	[0.017]	[0.015]	[0.014]*	[0.017]
Leverage	0.013	0.005	-0.008	-0.007	-0.011	0.001
	[0.018]	[0.018]	[0.020]	[0.020]	[0.019]	[0.023]
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm-RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
N	24450	24450	24450	24450	24450	24450
R2	0.011	0.005	0.011	0.013	0.005	0.015

Figure 1: Disclosed Climate Change Adaptation by Climate Risk Driver



Note: unit of analysis: firm-risk

Figure 2: Disclosed Climate Risk and Adaptation by Industry

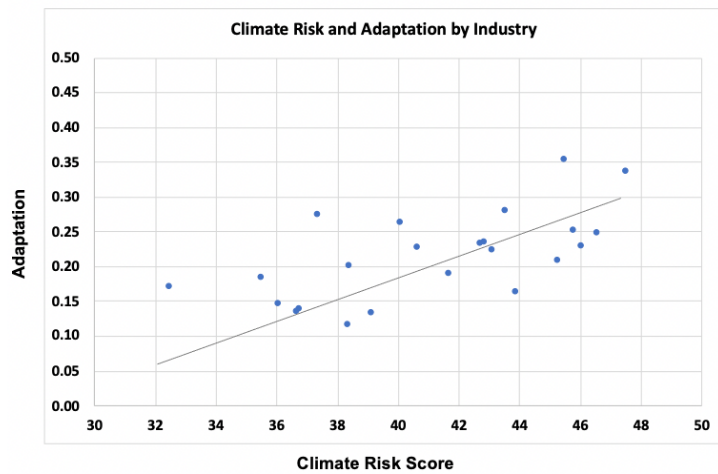


Figure 3: Disclosed Climate Change Adaptation by Year

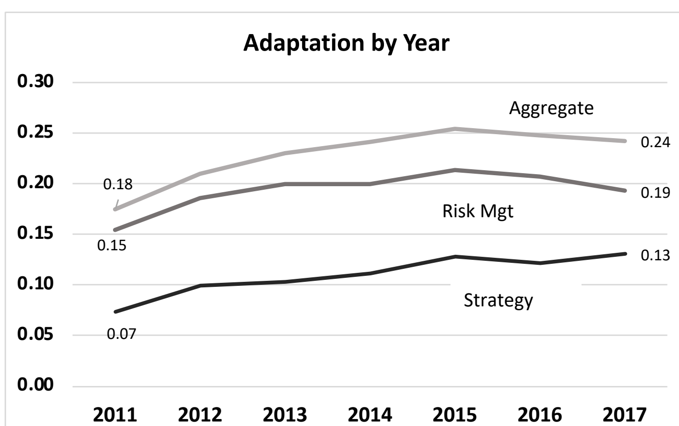
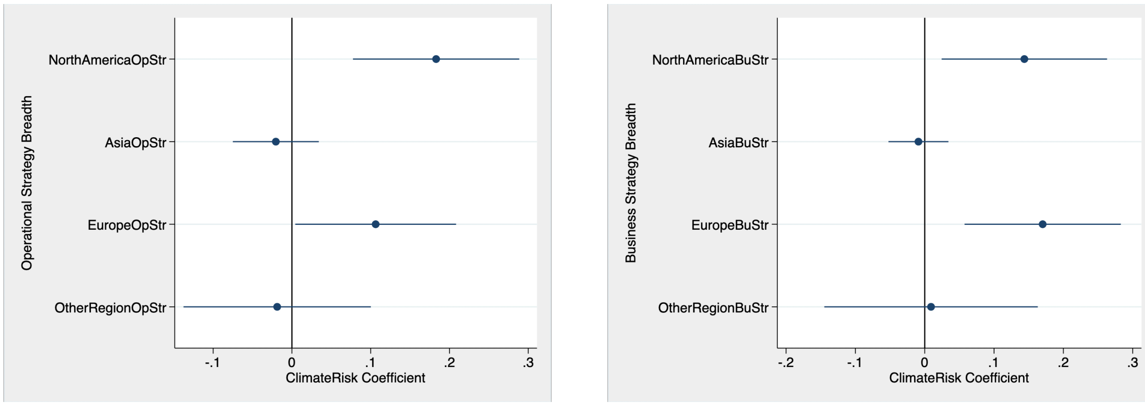


Figure 4: Climate Risk and Adaptation: Climate Risk Coefficients of Different Regions



Note: Different coefficients are run in separate regressions with country-year-industry fixed effect.

Online Appendix

Appendix A: Physical Climate Risk

In the study I collect firm-risk level physical climate risk data from Four Twenty Seven. Four Twenty Seven evaluates the degree and extent of climate change exposure based upon an ensemble mean of the outputs of five statistically downscaled Coupled Model Inter-comparison Project Phase 5 models selected from IPCC at specific locations where risk factors are measured. Each model provides projections that begin in 2020 and extend out to at least 2100. In order to understand how climate is expected to shift over time at a given location by comparing 2030-2040 projections against the historical baseline, Four Twenty Seven uses the period of 1975-2005 as a historical benchmark and projects future states in 2030-2040 under the "Business as Usual" greenhouse gas emissions scenario. It combines these projections with other environmental risk datasets to gain a comprehensive view of exposure to future climate risks given current conditions. Figure A.1 provides more methodology details for different climate risk drivers.

As most climate projection analysis, Four Twenty Seven's climate risk scores have several limitations. First, its evaluation of future extreme weather does not necessarily capture the most severe weather events. Second, it uses multi-model means which may under sample tail-end extreme events by missing processes below the resolution of the models (Tebaldi and Knutti 2007). Third, the model uncertainty also lies in modeling average shift in climate, although Four Twenty Seven applied statistical validation methods to account for model uncertainties and to ensure a practicable level of directional accuracy.

Physical climate risks of each company include that associated with firm's direct operations, its supply chains, as well as its markets. Four Twenty Seven also derives climate risk scores for each company that capture climate risks associated both with the supply chains that the company employs to drive its operations and the markets which consume the company's products. It evaluates the level of climate risk in a company's supply chain with its country of origin and resource demand scores. For market risk, each company is evaluated according to its country of sales and weather sensitivity. Due to data limitations, both supply chain and market climate risks are proxy scores evaluated at the country or industry level, and don't provide the same level of details as those provided by climate risks of firms' direct operations, which are based on facility information and disaggregated into different climate risk drivers. As such, the empirical analysis in the study focuses on the climate risks of firms' direct operations.

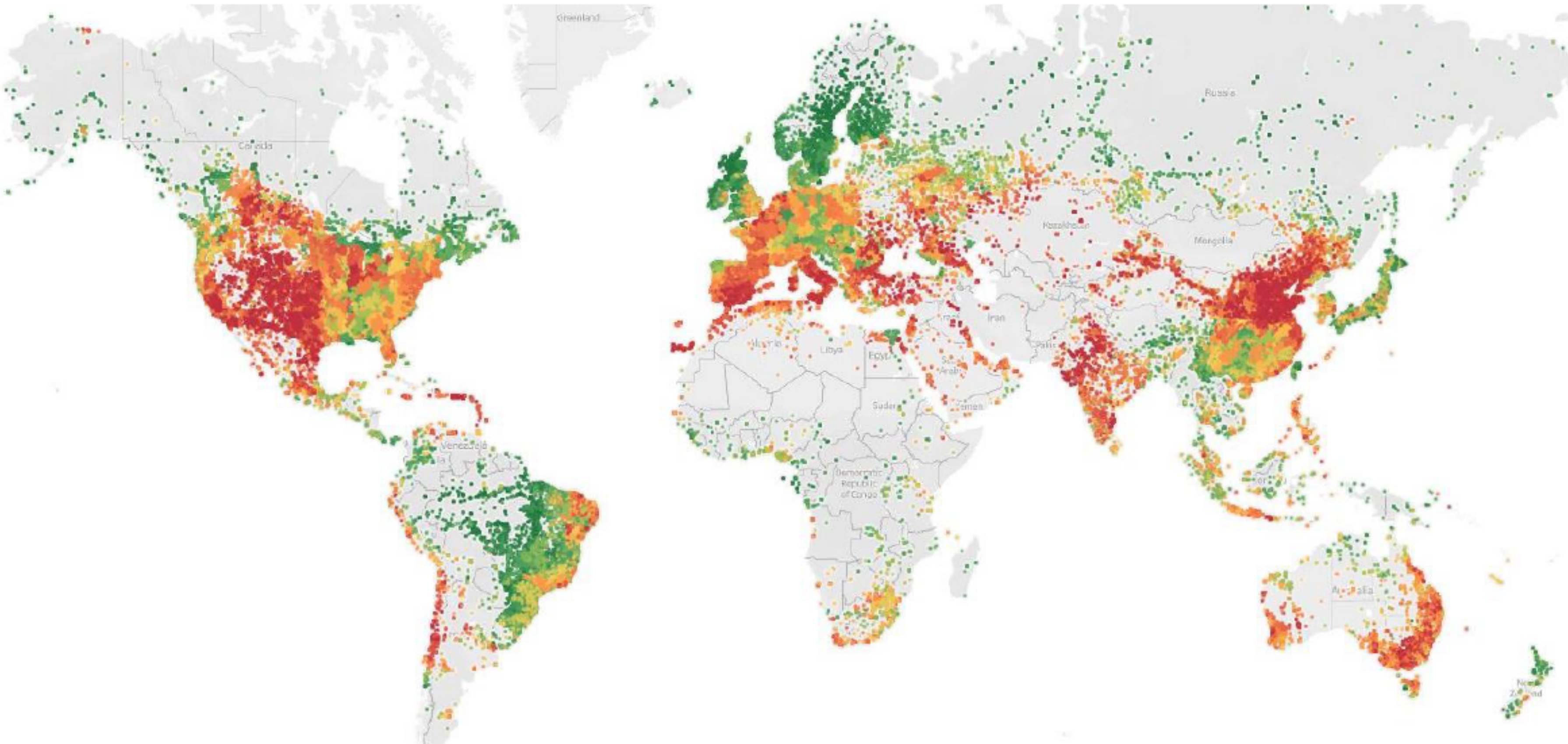
Climate risks of companies' direct operations are scored by aggregating the climate risks of each of their sites. Figure A.2 illustrates companies' exposure to water stress at the facility level. The company level water stress is aggregated by the water stress risk of each of its facility according to its activity type.

Figure A.1. Physical Climate Risk and 427 Methodology

Climate Hazards	Description	Spatial scale	Baseline period	Projection Period	Measurement
Floods	Change in rainfall conditions and size and frequency of possible floods	90 x 90 m (Flood) 25 x 25 km (Rainfall)	1975-2005 (Rainfall) 1985-2011 (Flood)	2030-2040 (Rainfall)	The flood score measures the severity and frequency of historical pluvial and fluvial floods, the frequency of future heavy rainfall events, and the intensity of prolonged periods of heavy rainfall. The flood frequency and severity indicators are based on a 1,000-year simulated history that was extrapolated from an observational history, and the rainfall indicators are based on global climate models.
Heat Stress	Increase in temperature	25 x 25 km	1975-2005	2030-2040	The heat stress score measures the relative change over time in the frequency and severity of hot days as well as in average temperature. Locations with high forecasted changes relative to recent history are most likely to be affected by temperatures unlike those previously experienced, even if these locations are not projected to experience the absolute warmest temperatures. Four Twenty Seven's analysis includes indicators related to changes in energy demand, changes in maximum temperature, and additional hot days.
Hurricanes and Typhoons	Exposure to past cyclones	25 x 25 km	1980-2016	N/A	The hurricanes & typhoons score captures geographic exposure to hurricanes or typhoons, also known as tropical cyclones. This cumulative measure reflects both the severity of storms with the highest maximum winds, but also the frequency with which an area has been subject to severe storms, excluding tornadoes and inland windstorms. Four Twenty Seven's uses a dataset of all recorded cyclones over the period 1980 and 2016. Only historical data is used, because global projection data is unavailable due to high uncertainty of how climate change influences tropical cyclone formation and intensity.
Sea Level Rise	Heightened storm surge, augmented by sea level rise	90 x 90 m	1986-2005	2040	The sea level rise score estimates the absolute and relative increase in the frequency of coastal floods. Estimates of sea level rise exposure are intended to capture: (1) the frequency of inundation due to a combination of sea level rise, storm surge, and high tides, and (2) change in the frequency of inundation between historical and projected periods. Estimates leverage global high resolution digital elevation model data as well as local storm surge and sea level rise estimates between 2017 and 2040. This analysis incorporates local flood risk statistics and local median sea level rise projections under carbon emissions scenario RCP 8.5.
Water Stress	Change in water supply and demand	Watershed	1950-2008	2040	The water stress score measures projected changes in drought-like patterns. It includes indicators that measure inter-annual variability, and absolute and relative percent changes in supply and demand for surface water (rainfall or rivers; not lakes or groundwater) available for consumptive use between the current period and 2040.

Note:Summary based on Four Twenty Seven Methodology

Figure A.2 Exposure to Water Stress for Facilities in Four Twenty Seven's Corporate Database



Note: Data from Four Twenty Seven. For illustrative purposes only

Appendix B: Firms' Disclosed Climate Change Adaptation Strategies

Figure B.1 Different Climate Change Adaptation Measures to the Same Climate Hazard

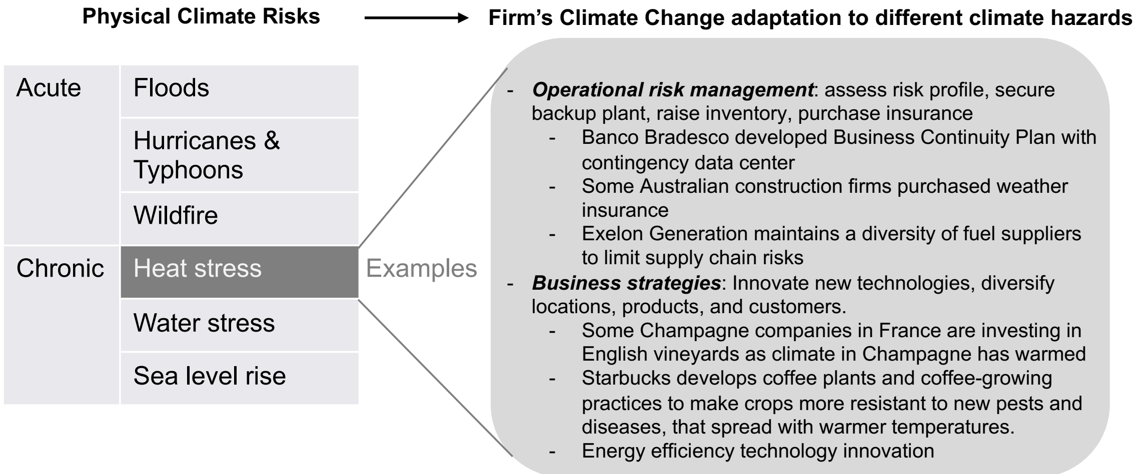
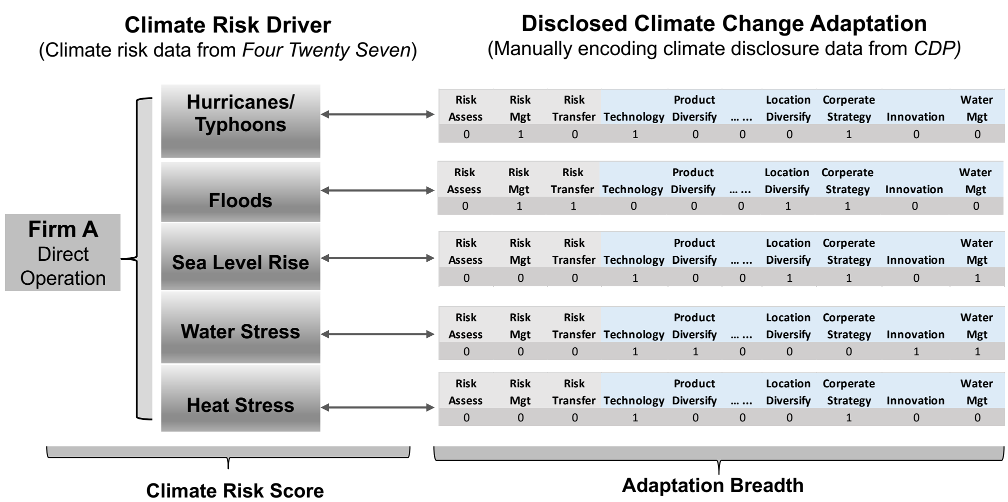


Figure B.2 Data Merging - Illustration from a Single Firm



Note: Climate Risk Scores range between 0 and 100. Adaptation Breadth is constructed by adding up adaptation categories (26 in total) the firms have taken in response to one climate risk driver.

Table B.1 Coding, Definition, and Example of Firms' Climate Change Adaptation Strategies

Type	Code	Definition	Example
Operational Strategies	Risk Assessment	Risk identification, monitoring, modelling, risk profiling	-Risk identification and review mechanism are in place. Half yearly and yearly review happened to address such a critical risk and accordingly prepare a road-map to manage such risk. -We manage this risk through our business continuity programs which incorporate risk assessment processes, emergency preparedness and disaster recovery and mitigation strategies. - We conduct a risk assessment in order to establish a support procedure for managing the situation in the event of any future floods.
	Risk Management	Safety management crisis/disaster management, loss prevention plan, Busniess Contituity Plan (BCP)	-We have business continuity plans (BCP) in place covering people, processes and technology. These are tested on a regular basis for survival and business critical activities. Crisis Management plans are exercised with extreme weather scenarios for locations with a history of extreme weather events. Specific extreme weather scripts have been developed in the APAC and the Americas regions To allow for efficient preparation of such events, Also for the smaller locations where no BC team is available. Additionally, contingency plans are being developed for weather related events, if it is felt that These events cannot be addressed by the standard BCP. - The methods used to manage this risks are: - business continuity and crisis management plans are in place, to prepare sites for potential disasters (minimising cost of. business interruption and maximising safety) and ensure ability to supply customers from from alternative locations. We have property loss programs have been developed to identify mitigation activities.
	Risk Transfer	Insurance and other financial instruments such as derivatives	-The company reviews property and business interruption insurance coverage regularly to make sure the business and its operations are adequately covered. - JBS seeks to assume advance purchase or financial derivative contracts for the purchase of agricultural commodities in order to manage their costs with feed ingredients. - We also purchase insurance cover for business interruption and loss which helps mitigate the financial impacts of extreme weather disruptions.
	Supplier Management	Supplier/pocurement diversification, sustainability	-To select a location for a new production facility, Toyota conducts empirical local climate study, with no exception, on impact from climate change such as floods and typhoons. Also, Toyota promotes "supply chain transparency" and "preparedness for disasters" as part of supply chain continuity management. Toyota develops its supply chain management system based on data provided from suppliers and performs risk analysis. The system helps us know what is happening to affected suppliers and prepare substitutional procurement and operation recovery at time of natural disaster. In addition, similar efforts that are integrated with suppliers are proceeding at production facilities in each country. - Have more diversified procurement practices to prevent dependency on one geographical region and/or supplier.
	Enterprise Risk Management	Development of holistic, top-down, enterprise view of all the significant risks that might impact business	- Raw Materials Sourcing integrated in the category management process and as part of Global / Enterprise Risk Management operations: - structured risk mitigation strategy, ("Windmill" process) to anticipate raw materials supply issues and suppliers deficiencies
	Buffer	Building more facilities; more stocks	-To mitigate the impacts of a natural disaster on our operations in Ohio, we separate our manufacturing capability across several buildings and created a separate production unit that creates a redundancy with our manufacturing process. -We have numerous redundancy systems and back-up protocols to ensure that no data is lost and all systems can operate without interruption
	Other Operational	Other operational measures	-Staff caring initiative such as operation of flexible work arrangement for site workers is conducted to protect the workers from the effects of heat. -Meeting peak summer demand is an integral part of network management and planning. Eversource electric operating companies produce annual integrated resource plans which anticipate and meet forecasted demands. Electric generating resources on the ISO New England grid are ample to meet predicted demand.
Business Strategies	Hard Technology	Adopting new/better EE technology/design/agri tech/water recycling tech	-A Zero Liquid Discharge (ZLD) system was installed at our San Luis Potisi, Mexico facility that produces vehicles and transmissions and is being operated to reuse water in the process, reduce withdrawal from deep wells, and reduce the risk of lack of water for production while providing an opportunity to continue production without interruption. The installed cost was $12M and ongoing operations are $200k -Exelon is also installing and using advanced smart grid and smart meter technologies to avoid outages and speed recovery. Smart grid technologies can help with early identification of outage location and specifics, as well as identification of equipment experiencing issues such that outages can be averted.
	Soft Technology	Adopting new IT system/tools, digital tech, platform etc.	-Furthermore, our ongoing IT server virtualization helps in the BCM environment to capture any potential loss of physically installed servers. Across all regions, we achieved a virtualization rate of 67% as per December 2017. IT server virtualization and consolidation across all regions has led to around 6.4 gigawatt-hours power consumption reduction across our Enterprise Data Centers for 2017. We expect more reduction on the longer term as our adoption of cloud and full-flash storage intensifies.
	Resilient inputs	Adopting more resilient inputs/seed/material	-To cope with changes of temperature that can cause extreme droughts which may affect quality, quantity and price of water intensive raw materials, Inditex is fostering the use of materials obtained from more sustainable sources and promoting use of best available techniques regarding minimum energy and water consumption. The raw material choices are closely intertwined with our biodiversity, water and energy management strategies. -For example, within the international tobacco business, we support farmers to manage climate and other forms of risk through programs to produce disease resistant tobacco leaf, financial assistance during incidents of natural disaster and via reforestation / sustainable tree planting programs. - We are analyzing climate models to assess the potential impact of changes in average temperature on plantations and to provide input to the development of adaptation strategies through our partnership with ETP and collaboration with Tea Research Association. The ETP and GIZ have formed a three year PPP to support climate change adaptation activities in the tea sector in Kenya, which has begun training approximately 10,000 vulnerable Kenyan farmers in the most appropriate adaptation techniques by 2016.
	Diversification of market	Targeting at different markets; investment in different markets	-To diversify and reduce direct risks such as high magnitude impact from climate change, the Group is entering into new business through M&A and expanding its business. As of 31st March 2017, Sompo Holdings completed the acquisition of Sompo International (formerly Endurance Specialty Holdings Ltd.) which has strength on agricultural insurance. -We maintain a diversified portfolio of customers in broad diversity of industries, thereby enabling us to mitigate risks associated with shocks to particular industries. Where some customers may be heavily impacted, other may realize gains.
	Diversification of product	Producing different products; diversified product mix; diversified technology	-We have diversified our product portfolio. Wessanen uses a large variety of commodities for example our dairy alternatives are based on soy, almond, oat, rice, spelt, etc.) and we monitor potential exposures of concentration in one single category. In general, Wessanen aims to mitigate volatility in commodity prices by frequently entering into term price agreements with suppliers, providing sufficient time to increase the selling prices of our products. We are managing the risks by closely monitoring pricing developments. In 2016 we acquired additional brands or companies to diversify our portfolio, such as 'El Granero' in Spain, 'Piramide Thee in Belgium' and 'Destination-Bio' thee in France.We are also building sustainable supply chains for key raw materials (cocoa, oat, almond and tea).
	Diversification of location	Building assets/factories at different locations to reduce physical exposure	-Lowe's operations are also widely distributed geographically in North America, so that local and regional climatic swings or extreme weather events are not likely to pose adverse extended impact to our operations. -Marine Harvest commits large resources to mitigation actions, together with neighboring companies in the various regions, cooperation with regulatory bodies to attain optimal regulations and efficient enforcement and geographical diversification of the salmon farming operations. - The risks identified as results of physical changes, can be mitigated by having a flexible and diversified winery in terms of vineyard selection and species, and a constant search for new areas to improve and diversify production.

* Correspondence: xiali7@bu.edu. I thank Tim Simcoe, Caroline Flammer, Andy King, Tom Lyon; and participants at SBE, SMS, and ARCS conferences for helpful comments. The author has no conflict of interest to report in connection with this research. All errors are the responsibility of the author.

Continued

Type	Code	Definition	Example
Business Strategies	Corporate Strategy	Considering climate issue when making Investment M&A,and JV decisions	-In 2020, we will spin-off our Upstream energy business, which is particularly exposed to physical climate risks to Gulf Coast suppliers which will reduce Ecolab's net exposure to suppliers' physical climate risks. -To diversify and reduce direct risks such as high magnitude impact from climate change, the Group is entering into new business through M&A and expanding its business. As of 31st March 2017, Sompo Holdings completed the acquisition of Sompo International (formerly Endurance Specialty Holdings Ltd.) which has strength on agricultural insurance. -AGL's integrated business strategy balances risk between upstream supply of energy and our customers' demand for energy. Vertical integration provides AGL with a natural hedge against energy price movements, whilst providing access to multiple profit pools. Horizontal integration through operating across the National Electricity Market provides further diversification of our earnings streams. The integrated business strategy, together with AGL's position as an early mover in renewable energy investment will act to mitigate risks related to peakier energy demand and associated price volatility
	Substitute	Self production vs. purchase; outsoursing	-Vertical integration provides AGL with a natural hedge against energy price movements, whilst providing access to multiple profit pools. Horizontal integration through operating across the National Electricity Market provides further diversification of our earnings streams. -To address the risk of raw material procurement due to the unusual weather, as in the examples, as a company that is ranked third in sales of tomato-processed products in the world, we have a large number of tomato farms and processing facilities around the world in addition to our own factories.
	Relocation	Relocation of factoies or headquarters	-Within the framework of this project / initiative, we verified a strategy to move the administrative headquarters of each CCR´s asset to geographic regions with greater security in relation to the availability of water, reducing the exposed of the assets to the risk of water deficit. - In 2016, Juniper made significant progress in managing risk related to sea level change by migrating portions of its HQ labs to Quincy, WA.
	Ecosystem-based adaptation (EbA))	Coorperating with ecosystems	-Example or case study If an unprecedented scale of typhoon hits the area where Kao Philippines is located, it is likely that neighboring rivers will overflow and the plant will be flooded at high tide, making it impossible to continue operating the equipment. To address this issue, we built a breakwater on the river side of the plant premises. In addition, we built a mangrove forest and breakwater on the coast line. -For example, at Thorpe Marsh Substation ditches ponds and wetland vegetation help to manage fluvial flood risks, active management of these natural features via a partnership with the Yorkshire Wildlife Trust. Practical actions such as ditch clearance and dredging has helped to retain ecosystem service functions. National Grid invested £30K over 3 years.
	Innovation	Research and Development; new product development; new technology development	-PGS is constantly developing technology that improves the robustness and efficiency of our operations. Examples of actions implemented is commissioning of our high-end Titan class Ramform vessels from 2014 to 2017 (final delivery) and developement of GeoStreamer technology. Both technologies enable us to continue safe and reliable operations during more adverse weather. -FMC continues to expand uses of the commercial on-planter application technology that minimizes labor, water use and fuel use. The patent-pending formulation and delivery system uses small amounts of water and expands the product three-dimensionally to cover 50 times more area than traditional formulations. It allows growers to plant and protect up to 500 acres on a single fill-up of the system and use 90 percent less water than traditional liquid delivery systems. FMC is formulating and testing active ingredients with this technology, including biological products. FMC allocated 82 percent of its 2017 R&D spend on developing sustainably advantaged products, which address global challenges like climate change, scarce resources, land competition, environmental consciousness and food & health expectations. - Our award winning environship design, and our advance and UltraFan next generation designs have been designed with consideration for likely changes in physical climate parameters, such as air temperatures. - Sumitomo Chemical is developing chemical agents that enhance the ability of plants to withstand factors preventing their growth, such as hotter, drier weather.
	Stakeholder Engagement	Engagement with Stakeholders such as communities and governments	-The Juice CSR Platform is a sustainability initiative for the fruit juice industry, which aims to support, guide and inspire stakeholders to integrate corporate social responsibility throughout the supply chain. The platform facilitates collaboration among all sector and supply chain stakeholders to address sustainability-related risks and opportunities. The Juice CSR Platform focused on three supply initiatives: identifying hotspots in the orange supply chain in Brazil and the apple supply chain from Poland and fostering dialogue with pineapple processors in Thailand. -We assess the vulnerability of our source-water at each production site and have implemented Source Water Protection Plans (SWPPs) for all our manufacturing operations in conjunction with water providers, government agencies, and community organizations.
	Energy Reduction	Energy Efficiency, reduce energy use, renewable energy	-Observing and Reporting asset level energy consumption internally. Improving internal managementEnergy saving actionsLong term investment planning processSharing best practicesCooperation with tenants & partnersEnvironmental certificates: BREEAM -Cellnex Telecom is already managing this risk and reduce refrigeration consumption, through several actions: 1- Implementation of projects related to weather information tracking, such as ENERTIKA Project, which focus on the management of energy consumption of Cellnex Telecom's communication centres and towers, by placing temperature sensors in the centres and track detailed weather, temperature and other information regarding the levels of consumption of every tower. Another example is the R&D+i SOLARE2RF Project-Powering and efficient cooling of radiofrequency sites
	Water Management	Reducing water use, recycling /reuse, seeking alternative water sources	-The initiatives are; reducing the amount of water used in the manufacturing process, recycling water used in manufacturing, and replenishing water resources.We align with the Source Water Protection guideline mandated by CCJC which aims to management of water source, secure sustainability of water resource, identification and mitigation of water risk, and respect to stakeholders. - Agriculture of the Future Project aims to promote the use of ecosystem approach and improve climate change adaptation. The program has saved 6.7 billion liters of water in 50.000.000 m2 areas of land.
	Climate Study	Climate specific assessment/study at the coporate level	- Since 2010, CLP has conducted a series of climate adaptation studies on existing power plants, starting with our fossil fuel plants and recently moving to our renewable portfolio. - Lockheed Martin partnered with Duke University to produce a report titled "Assessing Climate Change Vulnerability Across Lockhead Martin United States Facilities and Supply Chain Locations". The objective of this project was to assess the climate change vulnerabilities of the company's major facilities, as well as its Tier 1 and Tier 2 suppliers for one component of the C-130 military transport aircraft program. This report and the accompanying tool identifies climate change-related geographic factors, disruption vulnerabilities in existing facilities and supply chains, and adaptation strategies to ultimately determine vulnerability criteria for siting new facilities and setting up new supply chains.
	Other Strategies	Other business strategies	-Increased wildfire risk necessitates comprehensive statewide policy and operational solutions to policy and operations including: (1) Regulatory: updating compliance requirements in high-risk wildfire zones; (2) Legal: engaged in multiple forums to challenge the application of inverse condemnation at the trial, appellate, and state supreme court levels; (3) Legislative: advocating to address impacts of climate change and the need for comprehensive solutions to help the state adapt to meet the challenges of the "new normal"

Appendix C: Disclosed Climate Change Adaptation - Insights from Qualitative Evidence

To better understand the institutional context and to facilitate interpreting the results, I collect qualitative evidence about firm adaptation to climate risk from different sources. First, I interview 12 sustainability directors/consultants in the US and Asia. Second, I observe several climate risk seminars organized by regulators or industry professionals.[29] Third, I review CDP reports, sustainability reports, and annual financial reports of over 1,500 firms between 2010 and 2019 which provide textual information on firm adaptation to climate risk.

Among different industries, firms in mining, agriculture, and insurance sectors were the most likely to disclose physical climate risk and their adaption measures. For instance, Anglo American, a mining firm based in the UK, provided detailed climate risk analysis and strategies in annual reports, sustainability reports, CDP reporting, and specialized climate reports since 2010. Barrick Gold, a Canadian mining company, disclosed in CDP report that it implemented a Water Conservation Standard that requires all operations, closure sites and projects to monitor key conditions of climate and water resourced. It also adopted new nano membrane technology that provides water recovery from combustion processes. Many food and agriculture companies, such Starbucks, Tata Beverage, Coca-Cola, and FMC Corporation, have taken adaptation measures such as input resiliency, water use reduction, innovation, and cooperation with farmers. For instance, Coca-Cola İçecek disclosed that it developed Agriculture of the Future Project to improve climate change adaptation in agriculture, which has saved 6.7 billion liters of water in 50 million m^2 area of agricultural land. Philip Morris International researched drought tolerant seed varieties. Some insurers have responded to climate risks through new product development, M&A, and climate change modelling.

There are more firms disclosing physical climate risks and adaptation measures in recent years. For instance, Edison International started to disclose wildfire risks in 2017 and how it responds to these risks. Most firms adapted primarily through operational risk management in the early 2010s, as this sort of adaptation can be easily justified even if there is no climate change. One financial firm in Japan developed the BCP not only for climate risks but also "for a major earthquake that could strike Tokyo, or the potential outbreak of a new strain of influenza."[30]

Shifting business strategy is more difficult for companies compared with risk management, particularly if it involves changing the business direction, targeting different customers, or innovating alternative products. For example, one financial company targeting at low-income communities said in the interview that they cannot easily withdraw from their existing customers, although their climate change vulnerability is high.

The evidence revealed several inhibitors to adaptation action. First, because of the uncertainties inherent in differing climate change models, decision makers may have different views on the potential impacts when they assess climate information. For instance, one US retail company stated that "due to the lack of consensus on the magnitude and likelihood of sea level rise, the company is challenged to develop a strategy to reduce this particular risk."[31] Second, firms generally responded to natural disasters when they had experienced the impact of disasters directly, but they may not attribute the risk of disasters to climate change, and thus don't initiate climate related actions after these events have been resolved. For example, one utility company in the US responded to natural disasters such as drought through risk management procedures, but claimed that "we cannot predict whether long-term changes in frequency of severe weather

[29] Examples include GARP Climate Symposium and UNPRI. Discussants of "Building Resilience Against the Financial Risks of Climate Change" include Bank of England's Sarah Breeden, Hong Kong Monetary Authority's Arthur Yuen, the Federal Reserve Bank of New York's Kevin Stiroh; Colin Church, Global Head of Crisis Risk Management and Climate Risk, Citi; Alan Smith, Senior Advisor - Climate and ESG Risk Management, HSBC. Discussants of "Workshop on Integrating Climate Risks into Investment Portfolios" include HSBC's Global Head of Climate Change Centre of Excellence and VP Risk from BlackRock.

[30] Disclosure in CDP report. Accessed in August 2020.

[31] Disclosure in CDP report. Accessed in August 2020.

events due to climate change will have more of an impact on the electric distribution infrastructure than normal year to year variations in severe weather events."[30] Third, although extreme weather events may incur significant damages, their impacts are often be handled by property and liability insurance. One Sustainability Director of a financial firm in the US pointed out that "our firm has not paid attention to physical climate risk because the property insurance rate has not increased much even though we encountered several losses from floods."[32] As such, firms have few incentives to make strategic changes.

Despite all these challenges, there are some companies making strategic changes in response to high physical climate risk in the recent years. Landsec disclosed that it avoided acquisition of properties with close proximity to the coast, and dated coastal defenses, as sea level rise is expected to impact the coastal regions of the UK and could increase the likelihood of storm surge flooding. Vina Concha y Toro managed physical climate risk by having a flexible and diversified winery in terms of vineyard selection and species, and a constant search for new areas to improve and diversify production. In 2016, Juniper Networks made migrated part of its headquarter labs from Sunnyvale (CA) to Quincy (WA) to reduce seal level risk. In 2020 Ecolab spun-off its upstream energy business, which is exposed to physical climate risks of Gulf Coast suppliers. Rolls-Royces innovated more efficient product such as the Trent XWB engine, which is the world's most efficient large civil aero engine. The engine was designed with consideration for likely changes in physical climate parameters such as average air temperatures. Sumitomo Chemical developed chemical agents that enhance the ability of plants to withstand heat stress and drought that prevent their growth.

My interviews with managers revealed that many firms did not have relevant climate risk information at the granular level as conducting climate studies was costly and not considered urgent. Of the 1,500–2,000 public firms disclosing climate information to the CDP, less than 5% of them had conducted a climate-specific study by 2019. One Sustainability Director of a financial firm in the US said that "conducting the climate study is costly and not considered urgent."[33] There are, however, some firms taking the lead and studying the impacts of physical climate risk on their business. As disclosed in CDP reports, Lockheed Martin partnered with Duke University and produce a report "Assessing Climate Change Vulnerability Across Lockheed Martin United States Facilities and Supply Chain Locations" in 2015. Tata Global Beverages utilized climate models to assess the potential impact of changes in average temperature on plantations and to provide input to the development adaptation strategies through its partnership with ETP and collaboration with Tea Research Association. It supported climate change adaptation activities in the tea sector in Kenya, which has begun training approximately 10,000 vulnerable Kenyan farmers with appropriate adaptation techniques by 2016. In 2018, PG&E piloted beta versions of newly developed Climate Visualization and Screening tools on a significant transmission tower replacement initiative that is exposed to sea level rise.

Finally, my interviews revealed that stakeholders and shareholders play an important role in firms' decision-making process with respect to climate risk. One timberland investment manager said that "we have not paid much attention to adaptation because our shareholders are focusing on reducing GHG emissions so far."[34] In addition, many adaptation measures would need to involve neighbors and communities. For instance, one green building consultants said that "a shopping mall could be built to be climate resilient, but if its surrounding roads and housings are damaged by a hurricane, few people are able to go to the shopping mall after the event."[35] The evidence suggest that although the beneficiary of climate change adaptation are usually firms themselves, it may not be an easy task as it depends on partnership with stakeholders. As such, corporate governance and stakeholder engagement can help improve adaption.

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[32] Interview conducted on 21 May 2020.
[33] Interview conducted on 21 May 2020.
[34] Interview conducted on 14 May 2020.
[35] Interview conducted on 9 January 2020.

Appendix D: Additional Descriptive Results

Table D.1: Physical Climate Risks

Panel A: Climate Risk Score by Region

Region	Aggregate	HeatStress	WaterStress	SeaLevel	Floods	Hurricanes/ Typhoons
Asia	51.11	39.99	39.48	16.66	31.06	46.88
Europe	28.92	34.36	40.63	9.20	19.69	10.84
North America	35.24	42.40	47.27	8.32	19.18	17.62
Others	40.75	39.30	48.11	12.72	23.95	22.47

Panel B: Climate Risk Score by Industry

GICS Industry Group	Aggregate	HeatStress	WaterStress	SeaLevel	Floods	Hurricanes/ Typhoons
Insurance	32.50	33.45	39.34	9.31	17.86	23.65
Software & Service	35.51	36.20	45.71	11.89	18.62	21.12
Commercial & Pro	36.10	34.13	42.52	10.38	20.04	28.69
Health Care Equipment	36.70	38.87	44.05	9.11	21.13	23.66
Retailing	36.75	34.46	36.81	10.81	23.72	31.09
Telecommunication	37.35	40.80	37.91	10.60	23.37	21.74
Media & Entertain	38.36	34.24	45.41	13.30	22.85	25.16
Banks	38.39	39.65	41.91	13.36	20.81	22.23
Diversified Finanance	39.16	36.19	43.95	16.10	19.19	27.45
Energy	40.09	46.38	48.42	8.49	26.02	16.08
Household & Perso	40.65	39.25	41.58	10.58	27.25	28.94
Consumer Durables	41.69	36.81	38.05	11.55	26.08	38.12
Food & Staples Re	42.75	39.29	44.30	10.42	29.71	29.04
Pharmaceuticals,	42.87	38.05	44.51	12.81	26.37	32.63
Automobiles & Com	43.12	39.19	43.42	7.65	28.22	33.82
Consumer Services	43.56	40.14	41.01	17.29	25.84	30.82
Capital Goods	43.88	38.67	42.04	13.34	27.94	35.20
Semiconductors &	45.29	39.83	40.39	9.23	27.28	42.07
Utilities	45.51	49.54	46.83	10.32	28.64	25.07
Materials	45.80	42.10	44.02	13.25	28.08	34.79
Transportation	46.06	40.67	43.90	17.97	26.04	34.10
Technology Hardwa	46.57	38.78	39.40	11.24	30.35	42.64
Real Estate	47.53	43.52	45.00	22.50	21.47	32.30
Total	41.81	39.62	42.89	12.66	25.05	29.87

Note: Please note the aggregate climate risk score is not the average of different climate risk types, as Four Twenty Seven weighs different risk drivers differently for different industries, depending on their sensitivities to a particular risk.

Table D.2. Climate Change Adaptation Strategies (Firm-Climate Risk-Year)

Panel A: Firms' Climate Change Adaptation Strategies by Risk Driver

	Adaptation Dummy			Adaptation Breadth		
Climate Risk Driver	Aggregate	Operational Strategy	Business Strategy	Aggregate	Operational Strategy	Business Strategy
Cyclones	0.25	0.24	0.07	0.49	0.39	0.10
Floods	0.29	0.27	0.11	0.60	0.44	0.16
Heatstress	0.26	0.18	0.17	0.56	0.28	0.28
Sealevelrise	0.13	0.12	0.05	0.25	0.18	0.07
Waterstress	0.23	0.17	0.15	0.53	0.28	0.26
All	0.23	0.19	0.11	0.49	0.31	0.17

Panel B: Firms' Climate Change Adaptation Strategies by Region

	Adaptation Dummy			Adaptation Breadth		
Region	Aggregate	Operational Strategy	Business Strategy	Aggregate	Operational Strategy	Business Strategy
Asia	0.24	0.19	0.10	0.43	0.28	0.15
Europe	0.24	0.21	0.11	0.52	0.35	0.17
North America	0.21	0.18	0.11	0.47	0.30	0.17
Others	0.30	0.25	0.17	0.69	0.39	0.29

Panel C: Firms' Climate Change Adaptation Strategies by Year

	Adaptation Dummy			Adaptation Breadth		
Year	Aggregate	Operational Strategy	Business Strategy	Aggregate	Operational Strategy	Business Strategy
2011	0.18	0.15	0.07	0.36	0.25	0.10
2012	0.21	0.19	0.10	0.43	0.28	0.15
2013	0.23	0.20	0.10	0.48	0.33	0.15
2014	0.24	0.20	0.11	0.46	0.30	0.16
2015	0.25	0.21	0.13	0.57	0.35	0.22
2016	0.25	0.21	0.12	0.54	0.34	0.19
2017	0.24	0.19	0.13	0.53	0.31	0.22

Panel D: Firms' Climate Change Adaptation Strategies by Industry

	Adaptation Dummy			Adaptation Breadth		
Industry	Aggregate	Operational Strategy	Business Strategy	Aggregate	Operational Strategy	Business Strategy
Automobiles & Co	0.23	0.18	0.09	0.45	0.32	0.14
Banks	0.21	0.18	0.09	0.44	0.29	0.15
Capital Goods	0.17	0.14	0.07	0.32	0.23	0.10
Commercial & Pr	0.16	0.14	0.08	0.31	0.21	0.10
Consumer Durable	0.20	0.15	0.11	0.39	0.22	0.17
Consumer Service	0.29	0.22	0.15	0.54	0.31	0.23
Diversified Fina	0.14	0.13	0.06	0.30	0.19	0.10
Energy	0.28	0.25	0.12	0.58	0.40	0.18
Food & Staples R	0.24	0.20	0.15	0.57	0.31	0.25
Health Care Equi	0.14	0.13	0.04	0.27	0.21	0.06
Household & Pers	0.24	0.18	0.14	0.61	0.35	0.26
Insurance	0.18	0.17	0.07	0.42	0.32	0.09
Materials	0.26	0.23	0.13	0.55	0.35	0.20
Media & Entertai	0.12	0.07	0.08	0.23	0.10	0.13
Pharmaceuticals,	0.25	0.21	0.11	0.51	0.36	0.15
Real Estate	0.35	0.30	0.16	0.74	0.51	0.24
Retailing	0.14	0.11	0.08	0.29	0.17	0.12
Semiconductors &	0.21	0.18	0.11	0.46	0.30	0.16
Software & Servi	0.19	0.15	0.10	0.38	0.24	0.14
Technology Hardw	0.26	0.20	0.11	0.49	0.31	0.18
Telecommunicatio	0.29	0.24	0.13	0.62	0.38	0.24
Transportation	0.24	0.21	0.11	0.44	0.29	0.15
Utilities	0.38	0.32	0.24	0.95	0.55	0.40

Appendix E: Robustness Check – Climate Risk and Firms' Adaptation Strategies

Table E.1: Logit Analysis - Physical Climate Risk and Adaptation Dummy

	Adaptation Dummy	Operational Strategies Dummy	Business Strategies Dummy
ClimateRisk	0.163	0.202	0.114
	[0.039]***	[0.040]***	[0.050]**
Controls			
Size	0.362	0.371	0.331
	[0.067]***	[0.070]***	[0.083]***
Cash	-0.06	-0.086	-0.003
	[0.052]	[0.049]*	[0.060]
ROA	0.022	0.017	0.05
	[0.055]	[0.060]	[0.074]
Leverage	0.034	0.03	-0.028
	[0.043]	[0.047]	[0.059]
FirmAge	0.034	0.049	-0.036
	[0.044]	[0.045]	[0.053]
Diversity	0.027	0.021	0.028
	[0.059]	[0.060]	[0.071]
Multination	0.045	0.044	0.128
	[0.049]	[0.051]	[0.065]*
Risk FE	Yes	Yes	Yes
Country-Indust	Yes	Yes	Yes
N	24430	24395	24080

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Table E.2: Physical Climate Risk and Adaptation Breadth - Different Fixed Effects

	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.086	0.079	0.059	0.05	0.046	0.035
	[0.017]***	[0.016]***	[0.016]***	[0.015]***	[0.015]***	[0.013]***
Controls						
Size	0.091	0.086	0.058	0.13	0.122	0.084
	[0.020]***	[0.018]***	[0.018]***	[0.029]***	[0.028]***	[0.025]***
Cash	-0.035	-0.035	-0.02	-0.015	-0.025	0.004
	[0.017]**	[0.016]**	[0.015]	[0.016]	[0.015]*	[0.014]
ROA	0.047	0.037	0.039	0.035	0.026	0.031
	[0.023]**	[0.021]*	[0.018]**	[0.023]	[0.022]	[0.018]*
Leverage	0.035	0.028	0.029	0.016	0.019	0.005
	[0.018]*	[0.017]*	[0.016]*	[0.019]	[0.018]	[0.017]
FirmAge	-0.01	0.001	-0.019	-0.008	0.001	-0.017
	[0.018]	[0.018]	[0.016]	[0.017]	[0.017]	[0.014]
Diversity	0.051	0.036	0.049	-0.012	-0.01	-0.008
	[0.020]**	[0.020]*	[0.017]***	[0.023]	[0.022]	[0.021]
Multination	-0.011	-0.007	-0.011	0.024	0.016	0.023
	[0.020]	[0.017]	[0.020]	[0.020]	[0.017]	[0.020]
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	No	No	No
Industry FE	No	No	No	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	24450	24450	24450	24450	24450	24450
R2	0.057	0.051	0.051	0.052	0.044	0.05

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Table E.3 Physical Climate Risk and Adaptation Breadth – Different Control Variables

	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth
ClimateRisk	0.068	0.062	0.046	0.068	0.066	0.042	0.07	0.064	0.048
	[0.016]***	[0.015]***	[0.015]***	[0.016]***	[0.016]***	[0.016]***	[0.016]***	[0.015]***	[0.015]***
Controls									
Size				0.157	0.137	0.115			
				[0.029]***	[0.028]***	[0.025]***			
Cash				-0.042	-0.044	-0.023			
				[0.020]**	[0.019]**	[0.018]			
ROA				0.057	0.032	0.065			
				[0.035]	[0.032]	[0.027]**			
Leverage				0.005	0.006	0.003			
				[0.024]	[0.023]	[0.020]			
FirmAge							0.004	0.011	-0.007
							[0.023]	[0.023]	[0.018]
Diversity							0.08	0.065	0.065
							[0.023]***	[0.022]***	[0.021]***
Multination							0.025	0.014	0.028
							[0.025]	[0.021]	[0.025]
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	25515	25515	25515	24430	24430	24430	25515	25515	25515
R2	0.174	0.166	0.167	0.186	0.175	0.174	0.177	0.168	0.169

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table E.4 Physical Climate Risk and Adaptation Breadth – Cross-Sectional Analysis for Y2011 and Y2017

Panel A: Country-industry and Climate Risk Fixed Effects

	2011			2017		
	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth
ClimateRisk	0.079	0.063	0.074	0.108	0.096	0.078
	[0.024]***	[0.025]**	[0.025]***	[0.022]***	[0.024]***	[0.021]***
Controls						
Size	0.199	0.187	0.141	0.11	0.135	0.038
	[0.063]***	[0.057]***	[0.063]**	[0.029]***	[0.032]***	[0.028]
Cash	0.019	0.013	0.023	-0.06	-0.076	-0.017
	[0.052]	[0.047]	[0.050]	[0.021]***	[0.024]***	[0.021]
ROA	0.094	0.064	0.107	0.022	0.01	0.026
	[0.066]	[0.057]	[0.065]	[0.024]	[0.025]	[0.021]
Leverage	0.011	0.017	-0.003	-0.018	-0.022	-0.006
	[0.043]	[0.042]	[0.038]	[0.022]	[0.022]	[0.023]
FirmAge	0.014	0.019	0.001	0.009	-0.007	0.023
	[0.039]	[0.041]	[0.032]	[0.023]	[0.025]	[0.021]
Diversity	0.045	0.044	0.029	0.022	-0.015	0.054
	[0.049]	[0.046]	[0.050]	[0.026]	[0.026]	[0.027]**
Multination	-0.041	-0.06	0.007	0.059	0.04	0.057
	[0.038]	[0.032]*	[0.057]	[0.030]*	[0.026]	[0.031]*
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
N	2844	2844	2844	4054	4054	4054
R2	0.217	0.217	0.218	0.182	0.157	0.175

Note: Unit of analysis Firm-Risk. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Panel B: Firm and Climate Risk Fixed Effects

	2011			2017		
	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth
ClimateRisk	0.075	0.065	0.061	0.108	0.093	0.082
	[0.023]***	[0.024]***	[0.023]***	[0.022]***	[0.023]***	[0.021]***
Controls						
Size	0.075	0.039	0.105	0.142	0.048	0.188
	[0.049]	[0.052]	[0.045]**	[0.048]***	[0.055]	[0.038]***
Cash	-0.059	-0.102	0.036	0.057	-0.305	0.432
	[0.045]	[0.051]**	[0.040]	[0.046]	[0.048]***	[0.049]***
ROA	-0.007	-0.035	0.042	-0.169	-0.31	0.054
	[0.048]	[0.051]	[0.044]	[0.043]***	[0.050]***	[0.032]*
Leverage	0.002	-0.081	0.137	-0.076	-0.319	0.222
	[0.047]	[0.049]	[0.044]***	[0.047]	[0.051]***	[0.044]***
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
N	2845	2845	2845	4055	4055	4055
R2	0.011	0.006	0.015	0.037	0.041	0.055

Note: Unit of analysis Firm-Risk. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table E.5 Physical Climate Risk and Adaptation Breadth – Climate Risk in Log Form

	Model 1 - Polled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadth	Business Strategies Breadth
lnClimateRisk	0.105	0.109	0.059	0.101	0.102	0.059
	[0.017]***	[0.016]***	[0.016]***	[0.017]***	[0.016]***	[0.017]***
Controls						
Size	0.138	0.125	0.102	-0.03	0.033	-0.112
	[0.033]***	[0.032]***	[0.029]***	[0.057]	[0.057]	[0.074]
Cash	-0.047	-0.045	-0.027	0.002	0.007	-0.01
	[0.021]**	[0.019]**	[0.020]	[0.020]	[0.019]	[0.022]
ROA	0.048	0.028	0.065	-0.018	-0.019	-0.013
	[0.032]	[0.031]	[0.029]**	[0.019]	[0.018]	[0.021]
Leverage	0.003	0.002	-0.005	0.003	-0.004	-0.006
	[0.023]	[0.023]	[0.021]	[0.026]	[0.025]	[0.030]
FirmAge	0.005	0.007	-0.007			
	[0.022]	[0.022]	[0.019]			
Diversity	0.018	0.014	0.017			
	[0.026]	[0.025]	[0.025]			
Multination	0.014	0.003	0.033			
	[0.027]	[0.023]	[0.029]			
Country-Industry-Year	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	24430	24430	24430	24450	24450	24450
R2	0.188	0.18	0.174	0.036	0.033	0.038

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table E.6 Physical Climate Risk and Adaptation Breadth – Firm-level Analysis

	Adaptation Breadth		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.087	0.081	0.057
	[0.050]*	[0.048]*	[0.053]
Controls			
Size	0.226	0.21	0.169
	[0.039]***	[0.038]***	[0.038]***
Cash2	-0.045	-0.053	-0.012
	[0.028]	[0.026]**	[0.029]
ROA	0.019	0.009	0.027
	[0.031]	[0.031]	[0.029]
Leverage	0.022	0.03	0.015
	[0.029]	[0.028]	[0.028]
Year FE	Y	Y	Y
Country-Industry FE	Y	Y	Y
N	5378	5438	5438
R2	0.333	0.277	0.278

Note: Unit of analysis Firm-Year. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Appendix F: Robustness Check – ESG and Firms' Adaptation to Climate Risk

Table F.1 Environmental Strengths and Firms' Adaptation to Climate Risk (MSCI data)

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.076	0.074	0.046	0.068	0.067	0.041
	[0.017]***	[0.016]***	[0.016]***	[0.017]***	[0.016]***	[0.016]**
Env Score	0.031	0.02	0.031	-0.001	0.006	-0.01
	[0.023]	[0.021]	[0.022]	[0.010]	[0.010]	[0.011]
ClimateXEnv	0.032	0.023	0.031	0.029	0.019	0.029
	[0.011]***	[0.009]**	[0.011]***	[0.010]***	[0.008]**	[0.010]***
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	22760	22760	22760	22780	22780	22780
R2	0.192	0.178	0.18	0.03	0.029	0.037

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.2 Social Strengths and Firms' Adaptation to Climate Risk (MSCI data)

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.074	0.073	0.044	0.067	0.067	0.039
	[0.017]***	[0.016]***	[0.016]***	[0.016]***	[0.016]***	[0.016]**
Soc Score	-0.016	-0.015	-0.011	-0.015	-0.008	-0.017
	[0.031]	[0.026]	[0.029]	[0.015]	[0.015]	[0.014]
ClimateXSoc	0.026	0.024	0.017	0.021	0.019	0.014
	[0.011]**	[0.010]**	[0.011]	[0.010]**	[0.009]**	[0.010]
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Indu	Yes	Yes	Yes			
RiskDriver F	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	22760	22760	22760	22780	22780	22780
R2	0.191	0.178	0.179	0.03	0.029	0.036

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.3 Corporate Governance Strengths and Firms' Adaptation to Climate Risk (MSCI data)

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.073	0.072	0.043	0.065	0.065	0.038
	[0.017]***	[0.016]***	[0.016]***	[0.017]***	[0.016]***	[0.016]**
Gov Score	0.021	0.022	0.01	-0.001	-0.001	0
	[0.020]	[0.018]	[0.017]	[0.009]	[0.009]	[0.011]
ClimateXGov	0.005	0.006	0.001	0.001	0.003	-0.001
	[0.008]	[0.007]	[0.009]	[0.007]	[0.007]	[0.008]
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Indus	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	22760	22760	22760	22780	22780	22780
R2	0.191	0.178	0.179	0.029	0.028	0.036

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.4 Environmental/Social Strengths and Firms' Adaptation to Climate Risk

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.076	0.075	0.046	0.069	0.068	0.041
	[0.017]***	[0.016]***	[0.016]***	[0.017]***	[0.016]***	[0.016]**
Env+Soc	0.013	0.006	0.016	-0.010	0.000	-0.020
	[0.032]	[0.027]	[0.030]	[0.015]	[0.015]	[0.014]
ClimateX(Env+Soc)	0.035	0.028	0.03	0.03	0.022	0.028
	[0.012]***	[0.010]***	[0.012]**	[0.010]***	[0.009]**	[0.011]**
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry-Ye	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	22760	22760	22760	22780	22780	22780
R2	0.192	0.178	0.18	0.03	0.029	0.037

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.5 ESG and Firms' Adaptation to Climate Risk – 2011 MSCI Score only

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.077	0.074	0.048	0.069	0.067	0.042
	[0.017]***	[0.016]***	[0.016]***	[0.016]***	[0.016]***	[0.016]***
ESG2011	0.021	0.007	0.03			
	[0.033]	[0.031]	[0.029]			
ClimateXESG2011	0.046	0.029	0.048	0.039	0.023	0.043
	[0.015]***	[0.013]**	[0.016]***	[0.014]***	[0.012]**	[0.015]***
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry-Year	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	22760	22760	22760	22780	22780	22780
R2	0.193	0.179	0.181	0.031	0.029	0.038

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.6 ESG and Firms' Adaptation to Climate Risk – Net MSCI Score

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.076	0.074	0.046	0.068	0.068	0.04
	[0.017]***	[0.016]***	[0.016]***	[0.017]***	[0.016]***	[0.016]**
ESG Net	0.008	0.002	0.013	-0.006	0.001	-0.011
	[0.028]	[0.025]	[0.025]	[0.014]	[0.013]	[0.013]
ClimateXESG	0.031	0.026	0.024	0.026	0.021	0.022
	[0.011]***	[0.010]**	[0.011]**	[0.010]**	[0.009]**	[0.010]**
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Industry	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	22760	22760	22760	22780	22780	22780
R2	0.191	0.178	0.179	0.03	0.029	0.036

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.7 ESG and Firms' Adaptation to Climate Risk – ASSET4 data

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operationa l Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.083	0.08	0.051	0.075	0.073	0.045
	[0.018]***	[0.017]***	[0.017]***	[0.017]***	[0.017]***	[0.017]***
ESG	0.061	0.041	0.061	0.01	0.028	-0.016
	[0.019]***	[0.019]**	[0.017]***	[0.020]	[0.022]	[0.018]
ClimateXESG	0.028	0.017	0.03	0.024	0.013	0.026
	[0.009]***	[0.008]**	[0.010]***	[0.009]***	[0.008]*	[0.009]***
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Indus	Yes	Yes	Yes			
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	21930	21930	21930	21950	21950	21950
R2	0.192	0.181	0.178	0.031	0.029	0.036

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.8 ESG and Firms' Adaptation to Climate Risk – Sustainanalytics data

	Model 1 - Pooled Cross Section			Model 2- Firm Fixed Effects		
	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.078	0.075	0.049	0.072	0.07	0.044
	[0.018]***	[0.017]***	[0.018]***	[0.018]***	[0.017]***	[0.017]**
ESG	0.101	0.078	0.087	0.012	0.01	0.01
	[0.022]***	[0.022]***	[0.020]***	[0.018]	[0.019]	[0.020]
ClimateXESG	0.042	0.015	0.059	0.038	0.011	0.057
	[0.011]***	[0.011]	[0.012]***	[0.011]***	[0.010]	[0.012]***
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country-Indu	Yes	Yes	Yes			
RiskDriver F	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE				Yes	Yes	Yes
Year FE				Yes	Yes	Yes
N	21101	21101	21101	21120	21120	21120
R2	0.2	0.187	0.181	0.031	0.029	0.04

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table F.9 Physical Climate Risk and ESG

	ESGScore
ClimateRisk	0.002
	[0.005]
All Controls	Yes
Country-Year-Industry	Yes
RiskDriver FE	Yes
N	22760
r2	0.696

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Appendix G – Additional Analysis

Table G.1: Physical Climate Risk and Adaptation Strategies: Regional Differences

	Adaptation Dummy			Adaptation Breadth		
	Adaptation Dummy	Operational Strategies Dummy	Business Strategies Dummy	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.07	0.087	0.062	0.10	0.09	0.073
	[0.030]**	[0.028]***	[0.032]*	[0.029]***	[0.027]***	[0.033]**
ClimateXOther	-0.01	-0.029	-0.005	-0.024	-0.038	0.005
	[0.046]	[0.040]	[0.049]	[0.045]	[0.037]	[0.050]
ClimateXAsia	-0.013	-0.025	-0.052	-0.067	-0.045	-0.066
	[0.036]	[0.034]	[0.035]	[0.032]**	[0.031]	[0.035]*
ClimateXNAmerica	0.021	0.028	-0.006	0.008	0.02	-0.01
	[0.032]	[0.030]	[0.035]	[0.033]	[0.029]	[0.037]
Controls						
Size	0.139	0.136	0.107	0.152	0.136	0.115
	[0.026]***	[0.026]***	[0.026]***	[0.028]***	[0.028]***	[0.026]***
Cash	-0.044	-0.045	-0.025	-0.047	-0.046	-0.026
	[0.022]**	[0.020]**	[0.021]	[0.021]**	[0.019]**	[0.020]
ROA	0.036	0.025	0.061	0.049	0.028	0.066
	[0.027]	[0.028]	[0.028]**	[0.032]	[0.031]	[0.028]**
Leverage	0.008	0	-0.008	0.005	0.003	-0.002
	[0.021]	[0.022]	[0.021]	[0.023]	[0.023]	[0.021]
Country-Industry-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
N	24430	24430	24430	24430	24430	24430
r2	0.177	0.172	0.166	0.186	0.175	0.174

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table G.2. Physical Climate Risk and Adaptation Strategies – Influence of Climate Change and Risk Management Awareness

	Operational Strategy		Business Strategy	
	Operational Strategy Breadth	Operational Strategy Breadth	Business Strategy Breadth	Business Strategy Breadth
ClimateRisk	0.067	0.074	0.044	0.042
	[0.016]	[0.016]	[0.016]	[0.017]
ClimateXCCPI	-0.011		0.027	
(Climate Change Awareness)	[0.010]		[0.011]	
ClimateXInsurancePenetration		0.031		-0.003
(Risk Management Awareness)		[0.011]		[0.012]
Controls	Yes	Yes	Yes	Yes
Country-Year-Industry FE	Yes	Yes	Yes	Yes
RiskDriver FE	Yes	Yes	Yes	Yes
N	22298	24338	22298	24338
r2	0.176	0.175	0.178	0.174

Note: Unit of analysis is Firm-Risk-Year. *CCPI* is the Climate Change Performance Index for each country in a given year. *InsurancePenetration* is the country-level non-life insurance penetration rate. The country-year-industry fixed effects absorb the impacts of CCPI and Insurance Penetration. All variables are standardized to a mean of 0 and a standard deviation of 1 for easy interpretation. * p<0.10, ** p<0.05, *** p<0.01

Table G.3: Physical Climate Risk and Adaptation Strategies – Influence of GDP per Capita

	Adaptation Dummy			Adaptation Breadth		
	Adaptation Dummy	Operational Strategies Dummy	Business Strategies Dummy	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.085	0.096	0.054	0.085	0.096	0.054
	[0.020]***	[0.020]***	[0.019]***	[0.020]***	[0.020]***	[0.019]***
ClimateXGDPPC	0.011	0.016	0.005	0.011	0.016	0.005
	[0.012]	[0.011]	[0.013]	[0.012]	[0.011]	[0.013]
Controls						
Size	0.157	0.147	0.123	0.174	0.146	0.135
	[0.030]***	[0.031]***	[0.028]***	[0.034]***	[0.033]***	[0.028]***
Cash	-0.025	-0.031	-0.005	-0.024	-0.032	-0.003
	[0.025]	[0.022]	[0.023]	[0.022]	[0.021]	[0.020]
ROA	0.042	0.036	0.06	0.059	0.037	0.062
	[0.029]	[0.032]	[0.031]*	[0.039]	[0.036]	[0.031]**
Leverage	0.015	0.008	-0.003	0.017	0.017	0.011
	[0.024]	[0.025]	[0.022]	[0.027]	[0.026]	[0.021]
Industry-Country-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
N	20493	20493	20493	20493	20493	20493
R2	0.185	0.181	0.172	0.194	0.182	0.182

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Table G.4: Physical Climate Risk and Adaptation Strategies – Influence of Globalization

	Adaptation Dummy			Adaptation Breadth		
	Adaptation Dummy	Operational Strategies Dummy	Business Strategies Dummy	Adaptation Breadth	Operational Strategies Breadh	Business Strategies Breadth
ClimateRisk	0.079	0.092	0.05	0.086	0.081	0.055
	[0.020]***	[0.019]***	[0.019]***	[0.018]***	[0.018]***	[0.018]***
ClimateXKOFGI	0.012	0.014	0.014	0.022	0.018	0.018
	[0.012]	[0.010]	[0.011]	[0.011]**	[0.010]*	[0.011]
Controls						
Size	0.147	0.139	0.113	0.161	0.138	0.122
	[0.029]***	[0.029]***	[0.028]***	[0.032]***	[0.031]***	[0.027]***
Cash	-0.028	-0.032	-0.011	-0.028	-0.033	-0.01
	[0.024]	[0.021]	[0.023]	[0.021]	[0.021]	[0.020]
ROA	0.036	0.027	0.058	0.053	0.028	0.063
	[0.028]	[0.030]	[0.030]*	[0.037]	[0.035]	[0.029]**
Leverage	0.002	-0.004	-0.008	0.007	0.006	0.006
	[0.023]	[0.024]	[0.021]	[0.025]	[0.025]	[0.020]
Industry-Country-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
RiskDriver FE	Yes	Yes	Yes	Yes	Yes	Yes
N	22010	22010	22010	22010	22010	22010
R2	0.179	0.175	0.169	0.189	0.177	0.179

Note: Unit of analysis Firm-Risk-Year 2011 – 2017. Robust standard errors clustered at the firm level are in parentheses. * p<0.10, ** p<0.05, *** p<0.01

Appendix H – External Validity

Table H.1 S&P 500 companies with/without CDP climate risk disclosure

	S&P 500 Companies		
	Without CDP Disclosure	With CDP Disclosure	T-stat
HeatStress	42.15	43.04	1.28
WaterStress	47.69	47.53	0.21
Floods	18.82	20	2.07
SeaLevelRise	8.29	8.02	0.45
HurricanesTyphoons	17.19	18.1	1.40
Size	9.3	10.22	6.56
Cash	0.14	0.13	0.91
ROA	0.14	0.13	0.5
Leverage	0.3	0.32	0.91

Note: All S&P500 companies are requested to disclose climate information through CDP, and 64% of them provide physical climate risk information in 2019. 427 provided physical climate risk information to 94% of the companies in 2019.

Table H.2 Companies disclosing with CDP and with/without 427 physical climate risk data

	All Companies with CDP Disclosure		
	Without 427 Climate Risk Data	With 427 Climate Risk Data	T-stat
Size	8.03	10.04	26.62
Cash	0.13	0.13	0.27
ROA	0.11	0.11	1.02
Leverage	0.25	0.26	1.12
MSCI-ESG StrNum	0.28	0.48	6.52
MSCI-ESG StrNum - Control firm size			1.91

Note: MSCI-ESG StrNum-Control firm size are the results of comparing ESG strengths of firms with and without 427 scores by controlling for firm sizes.