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Marina Albanese, Guglielmo Maria Caporale, Ida Colella, and Nicola Spagnolo

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Marina Albanese[a] , Guglielmo Maria Caporale[b], Ida Colella[b] and Nicola Spagnolo [b, c, d]

[a] Dipartimento di Scienze Politiche, Universita' degli Studi di Napoli Federico II, Italy

[b] Department of Economics and Finance, Brunel University London, UK

[c] Centre for Applied Macroeconomic Analysis (CAMA), Canberra, Australia

[d,] Dipartimento di Economia, Universita' degli Studi della Campania Luigi Vanvitelli, Italy

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Abstract

This paper examines the impact of transition and physical climate risk on stock markets using, for the first time in this context, the annual CCPI index calculated by Germanwatch as well as its components (in addition to a wide range of other indices) for 48 countries from 2007 to 2023. Specifically, a balanced panel VAR model is estimated to obtain impulse responses for the whole set of countries considered as well as for a subset including the EU-28 only; other methods such as Forecast Error Variance Decomposition and Local Projections (Jorda, 2005, 2022) are then applied for robustness checks. The results suggest a positive impact of transition risk on stock returns and a negative one of physical risk, especially in the short term. Further, while physical risk appears to have an immediate impact, transition risk is shown to affect stock markets also over a longer time horizon. Finally, national climate policies seem to be more effective when implemented within a supranational framework as in the case of the EU-28.

JEL classification: C33, G12, G18

Keywords: Climate change; Physical risk; Transition risk; Stock markets; Balanced panel VAR; Impulse response analysis; Local projections.

Corresponding author: Professor Guglielmo Maria Caporale, Department of Economics and Finance, Brunel University London, Uxbridge, UB8 3PH, UK. Email: Guglielmo-Maria.Caporale@brunel.ac.uk; https://orcid.org/0000-0002-0144-4135

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1. Introduction

In recent decades climate change and global warming have become key issues for the planet Earth. To tackle their negative effects, various commitments have been made by world leaders at the UN Climate Change Conferences held regularly since 1995. In particular, a legally binding international treaty known as the Paris Agreement was signed by 196 countries at COP21 (Conference of the Parties 21) on 12 December 2015; this agreement set the goal of reducing greenhouse gas emissions to limit the temperature increase in the current century to 2 degrees Celsius, and also of adopting additional measures to bring it down further to 1.5 degrees.

Both climate change itself and policies aiming for a gradual shift from fossil fuels to renewable energy can have direct consequences for the economy and for financial markets. Bolton and Kacperczyk (2023) define "carbon transition risk" as "changes in climate policy, reputation impacts, changes in market preferences and norms, and technological innovation". More precisely, two types of risk might reduce the value of financial assets (see FBS, 2020): (i) "physical risks" due to the economic costs of weather events resulting from climate change, and (ii) "transition risks" arising from policies designed to promote an adjustment towards a low-carbon economy (see also OECD, 2021). There is some evidence that investors distinguish between the two (see Stroebel and Wurgler, 2021), and that the latter have a much greater impact on financial markets. [1] In an interesting study, Faccini et al. (2023) investigate whether either type of risk is reflected in US stock prices by conducting textual and narrative analysis of Reuter climate change news over the period 2000-2018. More specifically, they consider news releases in four different categories, i.e. natural disasters, global warming, international summits, US climate policy, and conclude that only the climate-policy factor is priced by investors and is reflected in the risk premium. Various other studies find that investors are unsure about how to price climate risk (see, e.g., Krueger et al., 2020), whilst climate legislation has significant effects on profitability (see, e.g., Ramadorai and Zeni, 2023; Bartram et al., 2022). It appears that climate risk in the form of possible policy interventions is priced in different types of assets such as stocks, bonds and options (see, *inter alia*, Ramelli et al., 2021: Bolton and Kacperczyk, 2021, 2023: Seltzer et al., 2022; Hsu et al., 2023).

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[1] See Giglio et al. (2021) for a thorough survey of the literature on climate finance.

Climate transition risk can affect individual economies but also spill over to others. As a result, financial institutions need to manage both domestic and foreign risk factors. Cross-border transmission could occur through the co-movement in risk premia on assets exposed to climate risk in different geographical areas, or through the exposures of financial institutions (see FSB, 2020). These issues are mentioned in various studies (e.g., Challinor et al., 2018: Benzie et al., 2019; Carter et al., 2021: Li et al., 2021; West et al., 2021), but none of them suggests ways to estimate spillovers across borders. By contrast, a recent paper by Yang et al. (2024) proposes a suitable framework to be used for this purpose. Their analysis measures climate risk as unexpected changes in the carbon risk premium, which is defined as "the return difference between companies with high-carbon emission and low-carbon emission". It examines company data in six markets (US, China, Europe, Canada, Australia and Japan) from 2013 to 2021, and provides evidence on both non-simultaneous and simultaneous transmission. The former is obtained by estimating a QVAR (Quantile Vector Auto Regression) model, whilst the latter is based on a PCA (Principal Component Analysis) approach. Two of their most interesting findings are that risk spillovers change over time and depending on the types of shocks, and that the transmission of information and economic linkages across countries are two of the main transmission channels.

As mentioned by Yang et al. (2024), an alternative way of capturing climate risk is to rely on existing indicators constructed on the basis of actual climate change data. This is the approach taken in the present study. More specifically, the analysis uses the Climate Change Performance Index (CCPI) calculated by Germanwatch, which measures transition risks and is available for 63 countries from 2007 at an annual frequency. [2] Studies using actual climate change data examine the extent to which countries have been affected by weather-related events such as storms, floods, heat waves etc. They are based on the concept of vulnerability as defined by the IPCC (2014), namely "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt". The CCPI instead assesses countries' efforts to combat climate change, with the set of countries included accounting for 90% of global greenhouse gas emissions. This index is based on standardised criteria applied to four categories, with 14 indicators: Greenhouse Gas Emissions (40% of the overall score), Renewable Energy (20%), Energy Use (20%), and Climate Policy (20%). To obtain further

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[2] See htpps://www.Germanwatch.org/en.

evidence on the impact of climate risk on financial markets we also use individual components of CCPI as well as a set of alternative climate indices found in the existing literature.

The empirical model is a balanced panel VAR including aggregate stock indices (as opposed to company data) for 48 countries over the period from 2007 to 2023, our aim being to examine the response of stock markets as a whole to climate change. Forecast Error Variance Decomposition and Local Projection methods (Jorda, 2005, 2023) are also applied to shed further light on the issues of interest. The estimation is carried out for the whole set of countries considered as well as a subset including the 27 European Union (EU) countries and the UK (which was a EU member for most of our sample period), the latter being a group of countries sharing supranational and binding climate policies which might affect the response of financial markets to climate risk.

The layout of the paper is the following: Section 2 reviews the literature on the impact of climate change on financial markets and on measures of climate risk; Section 3 describes the CCPI index as well as the alternative climate risk indicators used for the analysis; Section 4 outlines the empirical framework and discusses the empirical results, including robustness checks; Section 5 offers some concluding remarks.

2. Literature Review

This section provides an overview of the existing studies examining the effects of climate change on financial markets, and also of the different measures of climate risk proposed in the literature. For the convenience of the reader, the most relevant studies are also summarised in Tables 1 and 2.

Insert Tables 1 and 2 about here

2.1 Climate Risk and Financial Markets

Climate change poses a challenge to investors, namely accurately pricing climate risk and measuring climate risk premia (Bua et al., 2022) for various asset types such as bonds and equities (Lorente et al., 2023; Bua et al., 2022, Antoniuk et al., 2021). Hedging against climate risk might not be straightforward given the lack of universally accepted metrics for gauging firms' exposure to this type of risk and the challenge of estimating accurately the possible impact of specific climate events. In particular, investors may encounter difficulties in effectively screening firms that are vulnerable to climate risk, thereby possibly overlooking profitable investment opportunities. In general, one would expect investors to be inclined to accept lower expected returns for equities that appreciate when climate risk increases, as part of their risk management strategy. Consequently, stocks deemed "climate risky" should be expected to trade at a discount and to offer higher expected returns.

Engle et al. (2020) also emphasise that the inherent features of climate risk, such as its long-term nature and non-diversifiable characteristics, pose significant challenges to the development of traditional hedging instruments. In the presence of these challenges, individual investors find themselves primarily constrained to self-insure against climate risk, given the inadequacy of existing financial instruments for comprehensive risk mitigation. Battiston et al. (2021) argue that climate change may have wide-ranging effects on both corporate and sovereign bonds, the liabilities of insurance firms, the default rates on loans from financial institutions etc.

Ardia et al. (2023) point out that there are significant differences between customers, regulators, and investors in terms of preferences concerning sustainable solutions and climate-conscious investments. Moreover, these preferences can change over time in response to new information and evolving societal attitudes. Their dynamic nature has important implications for financial markets, as shifts in investor sentiment can have sizeable effects on asset prices: the latter may reflect not only market fundamentals, but also the evolving perceptions and preferences regarding climate change mitigation strategies.

Le Tran et al. (2023) analyse the different impact of physical and transition risk on financial markets. Specifically, they document the growing importance of physical climate risk for investors, as reflected by the return premium for firms with heightened exposure to this type of risk. By contrast, the return premium resulting from transition risk varies across industries and has shown signs of decline in recent periods. Pagnottoni et al. (2022) use a tailored event study methodology to analyse the effects of natural disasters in 104 countries on 27 global market indices. Their results suggest that climatological and biological hazards have the most significant negative impact on markets, while meteorological and hydrological disasters have weaker effects. Meinerding et al. (2024) find that transition risk affects widely the economy as a whole as well as financial markets, with sectors associated with fossil fuels being particularly vulnerable. This highlights the importance of policies aimed at mitigating the impact of transition risk, despite the fact that in the absence of frictions the transition toward a lower carbon economy should be expected to be smooth (the reason being that structural changes to achieve net zero emissions should be part of the information set of economic agents).

Faccini et al. (2023) use textual analysis to show that in fact only the climate-policy factor is priced by investors, especially after 2012. Their estimates of risk premium imply that investors hedge the transition risks from government intervention, as opposed to the direct risks from climate change itself. Textual analysis is also applied in the study by Yang et al. (2023b), who conclude that climate mitigation news are partially priced in the Canadian stock market; more specifically, they find asymmetric effects, namely stock prices react positively to market-wide climate-favourable news but not negatively to climate-unfavourable ones. Finally, Boungou and Urom (2023) find instead adverse effects of climate risk on banks' stock performance by applying a Quantile Regression method to daily stock index data for global and G20 banks.

2.2 Climate Risk Indicators

As already mentioned, the literature distinguishes between two types of climate risk, namely transition and physical risk, both of which affect especially countries lacking adequate resilience, coping mechanisms, or adaptation capacities to a green economy (Frege et al., 2023). Physical risk comprises both acute and chronic risk. The former denotes sudden, episodic occurrences capable of causing substantial physical harm, such as wildfires, river and ocean flooding, and tropical storms. The latter instead refers to on-going processes such as sea level rise and increases in global mean temperature (Buhr et al., 2022). In the case of financial markets, physical risk encompasses financial losses or higher expenses following chronic and acute physical events (Bua et al., 2022). Transition risk, on the other hand, stems from the process of transitioning to a low-carbon economy, which is influenced by factors such as regulatory changes, technological advancements, and shifts in social and market attitudes (Ardia et al., 2023).

It is noteworthy that there is currently a lack of consensus concerning the most appropriate measures for both physical and transition risk. Both GHG emissions (Ciccarelli et al., 2024, among others) and precipitation (Muntaz et al., 2024, among others) have been proposed as possible indicators for physical risk, whilst a wider range of measures have been developed for transition risk. As previously mentioned, a strand of the literature uses textual analysis to create indices based on news concerning climate change. For instance, Engle et al. (2020) extract innovations from climate news series and then use a mimicking portfolio approach to build climate change hedge portfolios. Bua et al. (2022) also develop physical and transition risk indicators based on textual analysis; these enable them to estimate climate risk premia, which are found to have increased since the Paris Agreement. Further, they consider various metrics to proxy a firm's exposure to either physical or transition risk. Ardia et al. (2023) construct a daily Media Climate Change Concerns index based on news about climate change published by major US newspapers and newswires, and find that, on days when negative climate change news are released, green firms' stock prices tend to increase, whereas brown firms' ones decrease in the case of both transition and physical climate change risk. Finally, Apel et al. (2023) calculate a Transition Risk Index through domain-specific vocabulary development, topic identification, and sentiment classification, using an extensive sample of newspapers.

On the whole, it is clear that textual analysis can indeed be informative, but it has the limitation of producing measures which are specific to the set of news and reports considered. For this reason, we use instead the aggregate Climate Change Performance Index (CCPI) calculated by Germanwatch as well as its individual components. Over the last few decades, the EU has implemented a series of policies and initiatives aimed at promoting the green transition and addressing climate change, and played a pivotal role in the Paris Agreement (2015). Therefore we are particularly interested in the Climate Policy component with the aim of investigating whether financial markets react favourably to EU climate-related policies being implemented and their targets being met (Horn, 2024).

Specifically, the Europe 2020 Strategy, launched in 2010, was designed to foster sustainable growth. One of its primary objectives was to reduce greenhouse gas emissions by 20% compared to 1990 levels, increase the share of renewable energy to 20% of total energy consumption, and enhance energy efficiency by 20%. The 2020 Climate and Energy Package, adopted in 2008, and the 2030 Climate and Energy Framework approved in 2014, set ambitious targets including a 40% reduction in greenhouse gas emissions (from 1990 levels), a 32% target for renewable energy, and a 32.5% improvement in energy efficiency.

Subsequently, targeted measures were implemented in line with the Paris Agreement. In particular, the European Green Deal (2019) represents one of the EU's most ambitious initiatives, aiming to make Europe the first climate-neutral continent by 2050. Key objectives include achieving a net reduction of greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, investing in clean technologies, reducing pollution, promoting the circular economy, and safeguarding biodiversity. The European Climate Law (2021) enshrines the objectives of the European Green Deal into law, providing the legal framework to achieve climate neutrality by 2050 and the interim goal of reducing emissions by 55% by 2030. In addition, the Climate Adaptation Strategy (2021) focuses on enhancing the EU's resilience to climate change impacts, including preparedness for extreme weather events and promotion of sustainable agricultural practices. Finally, in recent years, in response to the COVID-19 crisis, the EU has launched the Next Generation EU plan, with a significant portion of funding allocated to green projects. The Recovery and Resilience Facility supports reforms and investments by member states aimed at achieving a sustainable and resilient recovery.

3. Data Description

We use an extensive dataset consisting of yearly observations on stock market returns and several climate change indicators for 48 countries (see Table 3) over the period 2007-2023 (for a total of 816 observations). [3] These include the CCPI as well as other measures widely used in the literature. For the latter the choice of countries and the time span are driven by the availability of CCPI data in order to obtain comparable results. Table 3 reports the list of countries examined. The analysis is conducted for the whole dataset (48 countries), and also for the EU-28 (the EU-27 as well as the UK) countries, since the latter share a set of policies aiming at tackling climate change and global warming, for a total of 476 observations.

Insert Table 3 about here

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[3] The Climate Change Performance Index is produced for 63 countries. However, in order to have a balanced panel dataset, only countries for whom CCPI data were available for the whole time span (2007-2023) were selected. Hence, the number of countries considered for the empirical analysis is 48.

3.1 Climate Transition Risk Indicators

The database used for the analysis combines several variables coming from different sources. To capture the ability of countries to tackle the transition risk resulting from climate change, we use i) the Climate Change Performance Index (CCPI) from Germanwatch and ii) the Vulnerability Index from the World Risk Index, constructed by the United Nations University Institute for Environment and Human Security.

Insert Table 4 about here

The CCPI is an independent measure of countries' climate protection efforts, which provides transparency in international climate politics and facilitates cross-country comparisons. It is calculated for 63 countries that together account for more than 92% of global greenhouse gas (GHG) emissions (Burck et al., 2023). Evaluations based on the CCPI use standardised criteria to rank countries' climate performance. In particular, the CCPI assesses countries' progress towards the goal set by the Paris Agreement to reduce the global temperature increase well below 2°C, or even 1.5°C. It considers factors such as greenhouse gas emissions, renewable energy adoption, energy efficiency, and 2030 targets. The total CCPI score is made up of four categories: i) "GHG Emissions" (40% of the overall score), ii) "Renewable Energy" (20% of the overall score), iii) "Energy Use" (20% of the overall score) and iv) "Climate Policy" (20% of the overall score). These categories are further divided into subcategories.

In particular, it is possible to decompose GHG Emissions into 4 elements. 1) Current Level of GHG Emissions per Capita (10%); 2) Past Trend of GHG Emissions per Capita (10%); 3) Current Level of GHG Emissions per Capita compared to a well-below -2°C compatible pathway (10%); and 4) GHG Emissions Reduction 2030 Target compared to a well-below-2°C compatible pathway (10%) consistent with the Paris Agreement. We focus on the fourth component, which assesses countries on the basis of the proximity of their 2030 emissions reduction objectives to this trajectory. Those with more ambitious targets are given higher ratings reflecting a stronger commitment to climate policies.

Renewable energy also plays a crucial role in combating the global climate crisis by reducing greenhouse gas emissions and promoting energy efficiency. It can be broken down into 4 parts: 1) Current Share of Renewables per Total Primary Energy Supply (5%), that provides information about a country's carbon footprint and its contribution to addressing climate change. Countries are assessed differently depending on how their current greenhouse gas (GHG) emissions per person compare to the well-below-2°C compatible trajectory, those closely following this trajectory receiving better ratings and those with higher emissions per person lower ones; 2) Development of Energy Supply from Renewable Energy Sources (5%); 3) Current Share of Renewables per Total Primary Energy Supply compared to a well-below-2°C compatible pathway (5%); and 4) Renewable Energy 2030 Target compared to a well-below-2°C compatible pathway (5%).

The data on Climate Policies are instead produced annually through a comprehensive questionnaire. This comprises two sections focusing respectively on national and international climate policies. Their assessment relies on ratings provided by climate and energy policy experts from non-governmental organisations, universities, and think-tanks belonging to the countries under evaluation. Experts rate their government's performance in terms of the most significant measures, using a scale ranging from one ("weak") to five ("strong"). The survey asks specific questions with regard to Climate Policy National (10%) and Climate Policy International (10%). The former evaluates a country's policy effectiveness across six categories: i) GHG Emissions Reduction considering long-term low GHG emission development strategy (LTS - 2050), plan to phase out fossil fuel subsidies and carbon price signal; ii) Energy Supply and Renewable Energy that breaks into coal phase-out, gas phase-out and oil phase-out; ii) Energy Use includes transports and industry sectors and buildings; iv) NDCs - Future Targets 2030 survived into emissions reduction target, renewable energy target and energy use target; v) Non-Energy Sectors considers forestry, peat lands and agriculture and finally vi) Fossil Fuel Extraction and Infrastructure, composed by bans and phase-out of fossil fuel extraction, phase-out of fossil fuel subsidies for fossil fuel production and commitment to stop the expansion of fossil fuel infrastructure. As for the International Climate Policy component (weighted 10%), this is based on opinions concerning a country's participation to international events such as the G7, G8, UNFCCC, etc., with a final score, as for National Climate Policy, ranging from 1 (weak) to 5 (strong).

Finally, to measure transition risk we use the Vulnerability Index, which is a component of the World Risk Index.[4] This is an analytical tool designed to evaluate the potential for humanitarian disasters stemming from extreme natural events and the adverse effects of climate change across 193 countries. Rather than focusing only on the occurrence and severity of these events, it considers broader factors such as societal, political, and economic conditions. The basic model of the World Risk Index with its modular structure was developed by the United Nations University Institute for Environment and Human Security (UNU-EHS) and it provides a comprehensive assessment of the risk associated with extreme natural events and the adverse impacts of climate change. It employs a calculation method based on the geometric mean of exposure and vulnerability, with exposure encompassing various hazards such as earthquakes, tsunamis, floods, cyclones, droughts, and sea level rise. Vulnerability comprises three dimensions: 1) Susceptibility, 2) Lack of Coping, and 3) Lack of Adaptation. It specifically focuses on long-term processes and strategies aimed at proactively making changes in societal structures and systems to counteract, mitigate, or prevent future adverse impacts. The higher the score, the more vulnerable the country is.[5]

3.2 Climate Physical Risk Indicators

We have obtained from a variety of sources physical risk indicators for both chronic and acute risk as specified below.

Insert Table 5 about here

3.2.1 Chronic Risks

These are long-term risks that develop gradually over time and typically have a sustained impact. They often result from slow and persistent changes in environmental conditions. Chronic risks may include phenomena such as gradual sea level rise, ecosystem degradation, or slow environmental degradation due to pollution (Gagliardi et al., 2022). In order to capture this type of risks, we include two indicators, namely the Precipitation and the World Risk Index (exposure component). Precipitation data were taken from the Climatic Research Unit gridded Time Series (HadCRUT5 and CRU CY 4.07) dataset produced by the UK's

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[4] Since 2018 the report is published in cooperation with the Institute for International Law of Peace and Armed Conflict (IFHV) of the Ruhr-University Bochum.

[5] An Ordered-Quantile-Transformation was applied to prevent skewed distributions or outliers from skewing calculations, followed by normalization to a range of 0 to 100 (min-max normalisation).

National Centre for Atmospheric Science at the University of East Anglia (see Mumtaz et al., 2024).

3.2.2 Acute Risks

In contrast to chronic risks, acute risks are immediate, short-term events that occur suddenly. They are typically intense and may have an immediate and severe impact. Acute risks often stem from extreme weather and climate-related events, such as storms, floods, droughts, heat waves, wildfires, or other sudden natural disasters. While they may cause significant damage and disruption in the short term, their effects are generally short-lived compared to chronic risks. The data on heat waves, extreme precipitation, and droughts were taken from EM-DAT database. This records the type of natural disaster, the period when it occurred, the number of deaths, injuries and people affected by such extreme climate events. Following a similar approach to Caporale et al. (2018), we construct the following Acute Index per year/country:

$$AcuteIndex_{i,t} = \ln\left(e + \text{number of casualties}_{i,t} + \text{number of injured}_{i,t} + \text{number of people affected}_{i,t}\right), \quad (1)$$

where ln stands for the natural logarithm.

3.3 Dependent and Control Variables

We use annual stock market indices for 48 countries; the data source is Bloomberg. The selection of countries is driven by CCPI data availability. All 48 series are value weighted indices. We calculate stock returns by taking the first difference of their logarithm. Global stock markets uncertainty is proxied by the changes in the Chicago Board Options Exchange volatility index, known as VIX, which is a measure of implied volatility calculated using option prices on the S&P 500 index (this series is also obtained from Bloomberg). Several recent studies have documented the importance of changes in the VIX as a global factor affecting stock worldwide markets (Bouri et al., 2023). Furthermore, macroeconomic country-specific effects are controlled by including short-term interest rates (the 3-month policy rates) and real GDP growth (also calculated as the first difference of the log of the level series). For these variables the data source is the Federal Reserve Economic Data (FRED) website.

4. Empirical Analysis

To analyse the impact of climate risk shocks on stock market returns we obtain impulse responses (IRs) from a balanced panel Vector Autoregression (VAR) model specified as follows:

$$X_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_k X_{i,t-k} + Z_{i,t} + e_{i,t} \tag{2}$$

where $X_{i,t}$= ($\text{Stock Market Returns}_{i,t}$; $\text{Physical Risk}_{i,t}$ or $\text{Transition Risk}_{i,t}$, in turn); $X_{i,t-k}$ is a vector of lagged variables; $Z_{i,t}$ is a vector containing the VIX_t to control for global financial uncertainty, as well as real GDP growth and the 3-month policy rate to capture country-specific macroeconomic effects; $e_{i,t}$ is a residual vector following a multivariate normal distribution. Both the Akaike and Bayesian information criteria suggest an optimal lag length of 2 for all specifications.[6]

4.1 Benchmark Model Results

Table 6 provides descriptive statistics for all variables used. The yearly mean values (standard deviations) for all CCPI components are higher (lower) for the EU-28 countries, which suggest that these are better positioned for the transition to a green economy. The EU-28 are also less vulnerable (9.05) compared to the full sample (14.41). The climate physical risk indicators, on the other hand, imply that the EU-28 are less exposed to acute events than the whole sample, their respective mean values being 3.46 and 5.75. All variables appear to be stationary, I(0), as implied by the Levin–Lin–Chu (LLC), Levin et al. (2002), and Pesaran (2007) test statistics which are also reported in Table 6. In all cases the null hypothesis is that the series contains a unit root, and the alternative is that it is stationary.

Insert Table 6 about here

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[6] Panel-corrected standard errors (PCSE) are computed to account for possible cross-sectional dependence (Beck and Katz, 1995).

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Figure 1a displays for all 48 stock market return series the impulse responses (with the corresponding 95% confidence intervals) to a one standard deviation shock to the transition climate risk indicators (CCPI and its components). It can be seen that a shock to the CCPI total score has a positive but insignificant effect on stock market returns. When focusing on the components of CCPI, we find instead a positive and significant response over a two-year horizon to an international climate policy shock, whilst there is no evidence of any significant effects of national climate policy shocks. A plausible explanation for this finding is that investors perceive as effective only climate policies agreed and coordinated at the international level. Conversely, shocks to the GHG Emission have a negative and insignificant effect on stock market returns in the short run, consistently with the findings of Ardia et al. (2023), whereas markets respond positively in the medium run. As for shocks to renewable energy (i.e. the percentage of renewable energy over the total primary energy supply), their effect is positive and significant and lasts a couple of years. Finally, stock markets respond negatively to shocks to the Vulnerability Index.

Insert Figures 1a and 1b about here

The impact of physical risk shocks is estimated to be negative in all cases, but it is significant only for WRI. All IRs eventually converge towards zero, consistently with the behaviour of a stationary system. Finally, concerning the exogenous variables, an increase in the VIX volatility index has a significant negative effect on stock market returns, in line with previous empirical findings. The short-term interest rates are generally significant and with the expected negative signs in all estimated models, whereas GDP growth is generally found to have a positive effect on stock returns.

Next we discuss the results for the EU-28 countries only. Figure 2a displays the impulse responses of stock markets returns (with the corresponding 95% confidence intervals) to a one standard deviation shock to transition climate risk for this subset of countries. As before, shocks to international climate policies, renewable energy and GHG Emission are positively perceived by investors, but have a more sizeable impact in this case. Interestingly, shocks originating from national climate policies appear now to have a positive and significant effect on stock markets. This suggests that such policies have greater credibility if they are being followed in the context of a supranational framework. Lastly, shocks to vulnerability have a negative but insignificant effect.

Insert Figures 2a and 2b about here

Concerning the impact of physical risk (Figure 2b), again shocks to all three indicators have a negative effect on stock returns, but this is statistically significant only in the case of the Acute Index, consistently with the findings of Pagnottoni et al. (2022), who conclude that Europe is the continent with the greatest impact of natural disasters on financial markets. Again, all IRs eventually converge towards zero, as expected in a stationary system. The coefficients on the VIX and the short-term interest rates are mostly significant and negative, whereas GDP growth has a positively effect on stock returns.

4.2 Robustness Checks

We carry out various robustness checks. First, bootstrapped standard errors are computed; the IR confidence intervals are qualitatively the same and thus are not reported. As a second check we control for the global financial crises as well as the COVID-19 pandemic by constructing dummy variables taking the value of 1 during the following episodes: a) the Global Financial Crisis: 2007- 2009; b) the 2020-2021 (Covid-19 pandemic) crash, and 0 otherwise. These results (available upon request) are qualitatively similar to the previous ones and suggest that the VIX captures the impact of these shocks in all specifications. Third, we perform a Forecast Error Variance Decomposition (Table 5) over a 10-year horizon, which broadly confirms the IR findings. In particular, international climate policies shocks and the percentage of renewable energy over the total primary energy supply shocks account for a sizeable percentage of the forecast error variance of stock returns for the full sample as well as for the EU-28 only, whereas national climate policies shocks play a significant role only in the case of the EU-28 countries, consistently with our benchmark results. Finally, physical acute risk appears to be a key determinant of the forecast error variance of stock returns over the following two years.

Insert Table 7 about here

As a fourth and final robustness check, we estimate Local Projections following the approach of Jordà (2005, 2023). This involves running separate regressions for each time period following the shock, over the impulse response horizon. As in the case of the estimated VAR models, we calculate impulse responses for 10 years following a climate innovation. The baseline specification is as follows:

$$\mathrm{Returns}_{\mathrm{i,t+k}} = \alpha_{\mathrm{i,k}} + \beta_{\mathrm{t}}\mathrm{Climate\ Risk}_{\mathrm{i,k}} + Z_{i,t+k} + \mathrm{e}_{\mathrm{i,t+k}} \tag{3}$$

where $\mathrm{Returns}_{\mathrm{i,t+k}} = (\mathrm{Stock\ Market\ Returns}_{\mathrm{i,t+k}})$; $\mathrm{Climate\ Risk}_{\mathrm{i,k}} = (\mathrm{Physical\ Risk}_{\mathrm{i,k}}$ or $\mathrm{Transition\ Risk}_{\mathrm{i,k}}$, in turns); k stands for the number of periods after a reference year t; the vector $Z_{i,t+k}$ contains the global financial uncertainty index as well as real GDP growth and the 3-month policy rate to capture country-specific macroeconomic effects; $\mathrm{e}_{\mathrm{i,t}}$ is the residual vector. [7]

Insert Figures 3a and 3b about here

Figures 3a and 3b display the response of stock market returns (with the corresponding 95% confidence intervals) to a one standard deviation shock to each of our measures of climate change risk, for the full sample. Reassuringly, the results of the LP exercise are consistent with those obtained from the VAR models. For instance, international, but not national, climate policies are again found to have statistically significant effects lasting two years. It is important to note that LPs, in contrast to IRs, are not constrained to converge towards zero and therefore are expected to provide more accurate confidence intervals for longer horizons (Psaradakis et al., 2024). However, in our case we do not find any significant effects of the shocks considered over horizons longer than two years.

Finally, Figures 4a and 4b display the LPs for the EU-28 countries. On the whole, the results are again consistent with the IR ones. In particular, national climate policies appear to have a positive impact on stock markets, which is further evidence of their having higher credibility when being pursued within a supranational framework.

Insert Figures 4a and 4b about here

5. Conclusions

This paper examines the impact of transition and physical climate risks on stock markets in 48 countries using yearly data from 2007 to 2023. For this purpose a balanced panel VAR model is estimated to obtain impulse responses for the whole set of countries as well as a

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[7] Jorda (2023) discusses the pros and cons of estimating VARs vis-à-vis local projections.

subset including the EU-28 only, and then other methods such as Local Projections (Jorda, 2005, 2023) are applied as robustness checks. The contribution to the literature is twofold. First, ours is the first paper to use the CCPI index calculated by Germanwatch as well as its components to assess the impact of transition risk on stock markets. Second, it is the most thorough study to date on the consequences of climate change for stock markets since it analyses this issue for a very large set of countries and uses a wide range of indices for both transition and physical risk, thereby providing valuable evidence to investors and policymakers to make informed decisions during the on-going green transition.

Various empirical studies had already examined the impact of climate change on financial markets distinguishing between physical risk and transition risk (see, e.g., Pagnottoni et al., 2022; Bua et al. 2022), using textual analysis (Engle et al., 2020; Apel et al. 2023), or other physical and transition risk indicators (Boungou et al. 2023). Our findings are broadly consistent with earlier ones. In particular, they point to a positive impact of transition risk and a negative one of physical risk, especially in the short term (Bua et al., 2022). Moreover, transition risk is shown to have an effect only with a time lag, while physical risk appears to have an immediate impact. Our analysis also yields a number of new additional insights. More specifically, shocks to the Climate Policy index are shown to have a positive and significant impact, especially in the case of the EU-28 countries. This can be attributed to the coordinated efforts of a supranational organisation such as the EU towards achieving the green transition, exemplified by the European Green Deal (Horn, 2024). Further, we show that closer GHG to their 2030 emissions reduction objectives, reflecting a stronger commitment to climate policies, have a negative impact on stock market returns in the short-run, and a positive and significant effect, particularly for EU-28, at a longer horizon; this gives empirical support to the argument due to Le Tran et al. (2023), according to whom stricter emission regulations raise the cost of goods sold, thereby reducing profitability in the short-run.

By contrast, the Renewable Energy component generally has a positive impact, even for non-European countries, as global initiatives such as the Paris Agreement and subsequent United Nations efforts have promoted renewable energy usage through frameworks such as the International Investment Treaty Regime and Climate Action. The observed initial negative trends in the EU-28 are due to the transition costs and the longer timeframe required for benefits to materialise (Varun et al., 2009).

Finally, it is well known that climate change adversely affects the global economy, particularly through natural phenomena-induced physical risks (see Fabris, 2020). The World Risk Index (WRI) exposure component, reflecting geographical location and chronic climate physical risks, is found to have a negative impact on the EU-28 and on the full sample, albeit this effect is statistically significantly only for the latter. Instead, in the case of the acute index related to extreme natural disasters, our findings are consistent with earlier ones (see Pagnottoni et al., 2022, and Campiglio et al., 2023) suggesting that they have short-term negative effects, with the EU-28 stock markets being more exposed.

It should be acknowledged that the present study has some limitations arising from the low frequency and the aggregate nature of the climate risk indicators used. Future work should aim to gather additional evidence on the issues of interest by also examining the role of firm-specific characteristics such as industry, energy-intensity, renewable R&D activity, and expectations about future energy prices for the countries for which such data are available. This additional information would lead to a greater understanding of the impact of climate risk on different sectors with different degrees of readiness/vulnerability, and thus to the design of more effective sector-specific mitigation strategies.

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Table 1: Literature Review

Authors	Climate Indicators	Dependent Variables	Main Results
Engle et al., (2020). Review of Financial Studies	Physical (PRI) and Transition (TRI) climate risk indices constructed using textual and sentimental analysis	Equity returns data	The study finds that transition and physical risk premia in European equity markets have become more pronounced post-2015 (Paris Agreement) through mimicking portfolio approach.
Faccini et al., (2023). Journal of Banking and Finance	Climate risk index constructed using textual analysis	Stock market prices of all U.S. common stocks trading at NASDAQ and AMEX	The findings, using a standard portfolio approach suggest that it is government intervention risks, rather than the physical risks of climate change, that are not priced into the U.S. stock market.
Bua et. al., (2022). ECB Working Paper	Transition versus physical climate risk pricing in European financial markets: a text-based approach	Time-series data on European stock returns	The study, adopting a portfolio sorting approach, finds that transition and physical risk premia in European equity markets have become more pronounced post-2015. Investors assess companies' exposure to climate risks by considering factors such as greenhouse gas emissions, environmental performance, and ESG scores.
Apel et al., (2023). Finance Research Letters	Transition Risk Index constructed using textual and sentimental analysis	Returns of each index that capture the innovations in the Transition Risk Index	The study suggests a significant relationship between stock returns and short-term transition risk innovations using a regression analysis, especially for companies directly benefiting from increased transition risk
Ardia et al., (2023). Management Science	Climate Change Risk Index constructed using textual and sentimental analysis	Stock prices of green and brown firms of S&P 500	The findings suggest that even when people are more worried about climate change, environmentally friendly stocks might do better than less eco-friendly ones, even though they might usually have lower expected returns, as shown by regression analysis.
Bouri et al., (2023). Annals Operation Research	Physical (PRI) and Transition (TRI) climate risk indices developed by Bua et al., (2022).	Energy and technology stocks	The findings show, using a DCC GARCH Model, that clean energy stock prices have a much stronger response to physical risk shocks than technology stocks
Boungou et al., (2023). Economics Letters	Climate Risk Index constructed by Faccini et al., (2023).	Bank stock indexes representing the global and G20 country	The findings, through a Quantile Regression Model, indicate that international banks are facing losses as a consequence of worries regarding rising global temperatures and the frequency of natural disasters worldwide

Notes: This table presents a summary of the main studies discussed in the literature review section.

Table 2: Literature Review cont.d

Authors	Climate Indicators	Dependent variables	Main results
Yang et al., (2023). IMF Working Paper	Climate Transition Risk constructed using textual analysis	Canadian oil and gas companies in the Standard and Poor's (S&P500) TSX index and U.S. and EU companies	The findings from portfolio sorting approach consistently indicate that Canadian oil and gas companies' stock prices reflect climate mitigation risks. US and EU stock markets reveals a similar asymmetric response to climate-related news
Antoniuk et al., (2021). Journal of Sustainable Finance and Investment	Extreme climate events	Equity EFTs	The study, using the Patell's methodology, suggests that the stock market detects events that offer new insights into transition climate risks, prompting investors to quickly adjust prices.
Pagnottoni, et al., (2022). Physica A	EM-DAT data on natural disaster	Daily price returns for 31 major and geographic widespread stock indexes	The findings show, through a Seemingly Unrelated Regression (SUR), that the majority of geophysical events impact financial markets in a negative way.
Polat, et al., (2023). Journal of Climate Finance	Five MSCI Climate Change Indices (USA, EMU, Japan, Europe, and the Asia Pacific)	MCI for the four COVID-19 pandemic waves	Results reveal strong interconnectedness among indices, with spikes during major pandemic events. The study, using a TPVAR and frequency approach, shows that despite integration, hedging benefits from MSCI climate indices are minimal during crises. Short-term volatility connectedness is higher, indicating quick market responses to shocks and it decreases during the pandemic's later stages.

Notes: see the notes to Table 1.

Table 3: List of Countries – Full Sample

EU-28		NO EU-28	
Austria	Italy	Australia	Mexico
Belgium	Latvia	Brazil	Morocco
Bulgaria	Lithuania	Canada	New Zealand
Croatia	Malta	China	Russia
Cyprus	Netherlands	Egypt	Saudi Arabia
Czech Republic	Norway	India	South Africa
Denmark	Poland	Indonesia	South Korea
Estonia	Portugal	Japan	Thailand
Finland	Romania	Kazakhstan	Turkey
France	Slovenia	Malaysia	United States
Germany	Spain		
Greece	Sweden		
Hungary	Switzerland		
Ireland (Republic of)	United Kingdom		

Notes: The EU-28 includes the EU-27 countries as well as the UK, namely countries which have been sharing a set of policies aiming at tackling climate change and global warming.

Table 4: Climate (Transition) Risk Indicators, Sources and Descriptions

Indicator	Source and Sample	Definition
CCPI	Germanwatch 2007-2023	It assesses and compares the climate performances of a wide range of economies, promoting transparency and action against climate change. It is a tool that evaluates countries' mitigation efforts in response to climate change.
CCPI components		
National Climate Policy	Germanwatch 2007-2023	Government's performance towards national policies.
International Climate Policy	Germanwatch 2007-2023	Country's participation to international events such as the G7, G8, UNFCCC.
GHG Emission	Germanwatch 2007-2023	This component refers to the emission's reduction 2030 Target compared to a well-below-2°C compatible pathway and it assesses countries on the basis of the proximity of their 2030 emissions reduction objectives to this trajectory.
Renewable Energy	Germanwatch 2007-2023	This category information about a Current Share of Renewables per Total Primary Energy Supply
Vulnerability	World Risk Index (UNU-EHS) 2000-2023	Vulnerability refers to the susceptibility of populations to damages following extreme natural events or climate change impacts. It comprises susceptibility, lack of coping, and lack of adaptive capacities.

Notes: This table presents a summary of the main climate risk indicators discussed in the data description section.

Table 5: Climate (Physical) Risk Indicators, Sources and Description

Indicator	Source and Sample	Definition
		Chronic Risk
%Precipitation	Climate Research Unit 1901-2023	This variable is related to percentage anomalies, so the lowest possible value would be -100, i.e. no rain. The values expressed are monthly and annual.
WRI (Exposure)	World Risk Index (UNU-EHS) 2000-2023	It measures the exposure to various hazards like earthquakes, tsunamis, floods, cyclones, droughts, and sea level rise.
		Acute Risk
Heat waves, extreme precipitation, droughts	EM-DAT 1901-2024	It contains information about the type of extreme natural disasters, the number of deaths, injuries, and affected people.

Notes: see the notes to Table 4. Precipitation is found to be not stationary. Therefore, %Precipitation is used and calculated as the year-on-year change in precipitation.

Table 6: Descriptive statistics and Unit Roots Tests

	Full Sample				**EU-28**			
	Descriptive Statistics							
Variables	**Mean**	**S.D.**	**Min**	**Max**	**Mean**	**S.D.**	**Min**	**Max**
Stock Returns	6.06	24.89	-79.71	93.56	4.37	22.21	-59.22	73.39
Interest rate	3.16	4.11	0	39.21	2.43	3.46	0	8.2
GDP growth	2.22	5.78	-27.83	29.32	1.68	3.99	-14.83	24.47
VIX	20.09	6.25	11.09	32.69	20.09	6.25	11.09	32.69
	Climate Transition Risk							
CCPI	52.21	10.52	8.81	73.40	56.11	7.61	37.01	79.61
Policy National	4.80	2.33	0	10	5.01	2.23	0	10
Policy International	4.98	2.51	0	10	5.36	2.36	0.14	10
Renewable	0.27	0.23	0	1	0.30	0.22	0	1
GHG Emission	0.56	0.22	0	1	0.59	0.17	0.16	1
Vulnerability	14.41	9.93	2.79	57.81	9.05	3.31	2.29	20.23
	Climate Physical Risk							
%Precipitation	849.36	609.51	0	3504	758.53	321.09	0	1527
WRI	10.18	10.73	0.78	45.61	3.47	2.44	0.74	10.01
Acute Index	5.75	4.95	0.99	19.62	3.46	3.13	0.99	14.68
Observations	816				476			
Countries	48				28			

Panel Unit Root Tests

	LLC		**Pesaran**		**LLC**		**Pesaran**	
	T. Stat.	p-value	T. Stat.	p-value	T. Stat.	p-value	T. Stat.	p-value
Stock Returns	-26.35	0.000	-25.82	0.000	-23.11	0.000	-20.13	0.000
Interest rate	-30.49	0.000	-8.92	0.000	-30.11	0.000	-7.23	0.000
GDP growth	-20.65	0.000	-16.66	0.000	-16.98	0.000	-12.35	0.000
CCPI	-5.59	0.000	-4.69	0.000	-5.45	0.000	-4.33	0.000
Policy National	-9.78	0.000	-6.92	0.000	-5.37	0.000	-4.71	0.000
Policy International	-6.94	0.000	-4.95	0.000	-4.06	0.000	-2.41	0.008
Renewable	-15.21	0.000	-12.83	0.000	-5.11	0.000	-4.32	0.000
GHG Emission	-8.98	0.000	-7.44	0.000	-4.56	0.000	-3.99	0.000
Vulnerability	-9.77	0.000	-5.87	0.000	-6.22	0.000	-4.12	0.000
%Precipitation	-8.83	0.000	-6.78	0.000	-6.44	0.004	-4.15	0.000
WRI	-8.96	0.000	-5.99	0.000	-6.21	0.000	-3.77	0.000
Acute Index	-15.12	0.000	-13.04	0.000	-3.66	0.000	-2.41	0.000

	ADF				**ADF**			
VIX	-30.16	0.000			-30.16	0.000		

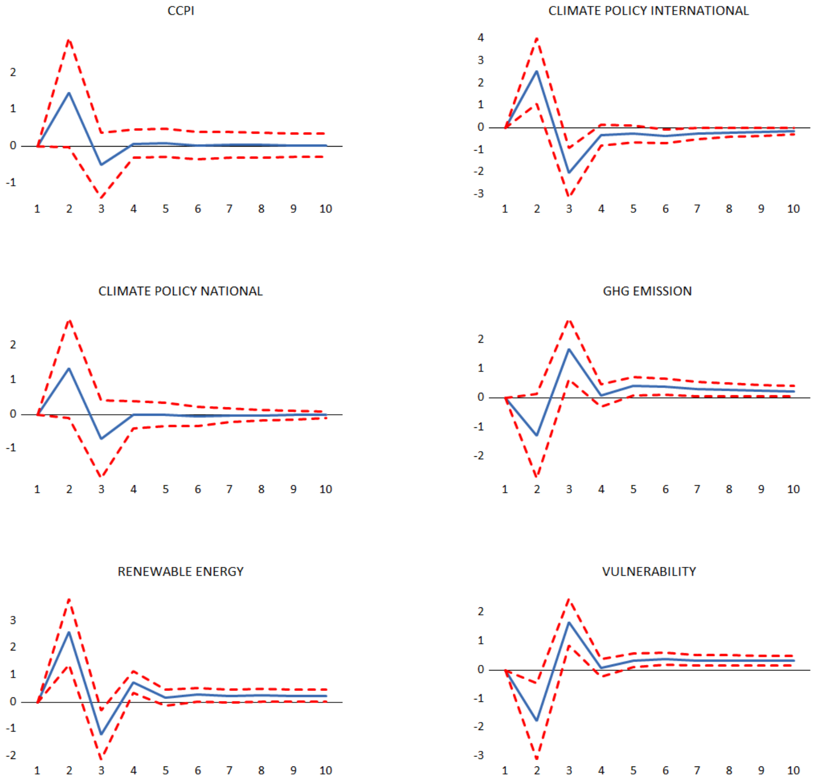
Notes: The sample size covers the period 2007-2023. S.D. stands for standard deviation. LLC and Pesaran refer to Levin et al. (2002) and Pesaran (2007) unit root tests, respectively. LLC (Pesaran) tests set the null hypothesis that the series contains a common (individual) unit root process, and the alternative that the series is stationary. The VIX does not have a longitudinal dimension; therefore stationarity is computed by means of the ADF test.

Table 7: Forecast Error Variance Decomposition

	Full Sample				**EU-28**			
	Stock Returns		**Climate Risk**		**Stock Returns**		**Climate Risk**	
				Transition Risk				
CCPI$_{t-1}$	**99.01**	(1.43)	0.99	(1.77)	**99.67**	(2.09)	0.33	(0.66)
CCPI$_{t-2}$	**99.03**	(1.55)	0.97	(1.54)	**99.49**	(1.77)	0.51	(1.01)
Policy nat$_{t-1}$	**98.72**	(1.94)	1.28	(0.98)	**98.24**	(1.49)	**1.76**	(0.64)
Policy nat$_{t-2}$	**98.22**	(1.23)	1.78	(1.11)	**98.18**	(0.99)	**1.82**	(0.69)
Policy int$_{t-1}$	**99.43**	(1.25)	**0.57**	(0.16)	**98.22**	(0.79)	**1.78**	(0.48)
Policy int$_{t-2}$	**99.25**	(1.47)	**0.75**	(0.33)	**98.34**	(1.96)	**1.66**	(0.57)
Renewable$_{t-1}$	**98.38**	(1.25)	**1.62**	(0.57)	**98.53**	(2.21)	**1.47**	(0.38)
Renewable$_{t-2}$	**98.04**	(1.47)	**1.96**	(0.81)	**98.22**	(2.42)	**1.78**	(0.77)
GHG Emission$_{t}$	**99.60**	(1.92)	0.40	(0.44)	**99.21**	(2.02)	0.79	(1.22)
GHG Emission$_{t}$	**98.82**	(1.98)	1.18	(1.01)	**99.19**	(0.88)	0.81	(1.33)
Vulnerability$_{t-}$	**99.25**	(1.44)	**0.75**	(0.21)	**99.68**	(1.25)	0.32	(0.99)
Vulnerability$_{t-}$	**98.43**	(2.33)	**1.57**	(0.67)	**98.23**	(1.89)	0.77	(0.94)
				Physical Risk				
Precipitation$_{t-}$	**99.94**	(1.22)	0.06	(0.23)	**99.98**	(1.82)	0.02	(0.99)
Precipitation$_{t-}$	**99.80**	(1.66)	0.20	(0.45)	**99.96**	(1.66)	0.04	(0.79)
WRI$_{t-1}$	**98.69**	(1.05)	**1.11**	(0.42)	**99.74**	(1.45)	0.26	(1.76)
WRI$_{t-2}$	**98.21**	(1.22)	**1.79**	(0.88)	**99.69**	(2.02)	0.31	(1.11)
Acute$_{t-1}$	**99.89**	(1.05)	0.11	(0.56)	**98.40**	(1.07)	**1.60**	(0.61)
Acute$_{t-2}$	**99.37**	(1.46)	0.63	(1.06)	**98.31**	(1.55)	**1.69**	(0.53)

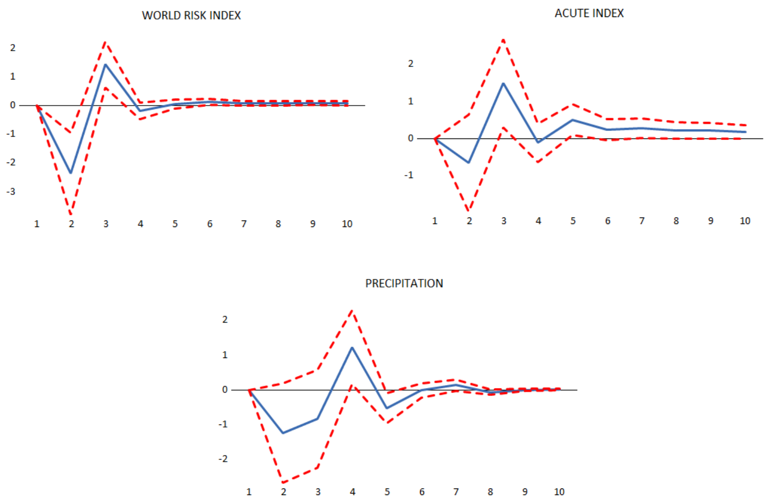
Notes: The entries measure the contribution of the climate shocks, and stock returns, to the forecast error variance of stock returns in each estimated model, with stock market returns being the dependent variable. Akaike and Bayesian information criteria selected two lags for all VAR model specifications. WRI captures countries' exposure to physical climate risk. Standard errors are computed by means of 10,000 Monte Carlo simulations and reported in brackets. Parameters significant at the conventional 95% are reported in bold.

Figure 1a: IR of stock market returns to climate (transition) risk shocks – Full sample



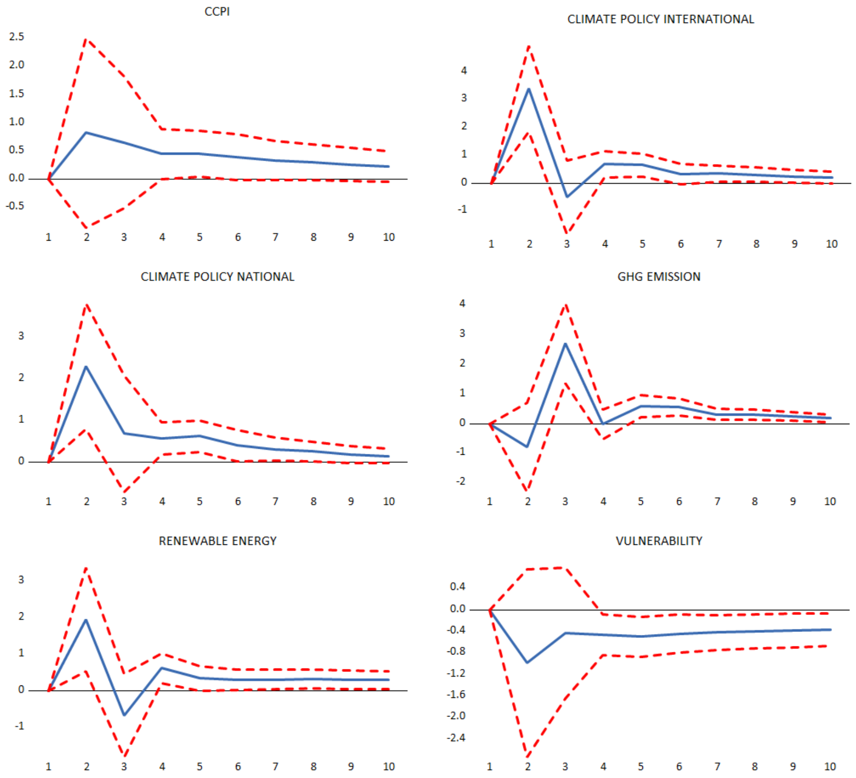
Notes: The sample includes 48 countries, reported in Table 5. The blue line is the Impulse Response (IR), whilst the red dotted lines are the 95% confidence interval. Responses refer to Cholesky one standard deviation innovations. Standard errors are computed by means of 10,000 Monte Carlo simulations.

Figure 1b: IR of stock market returns to climate (physical) risk shocks – Full sample



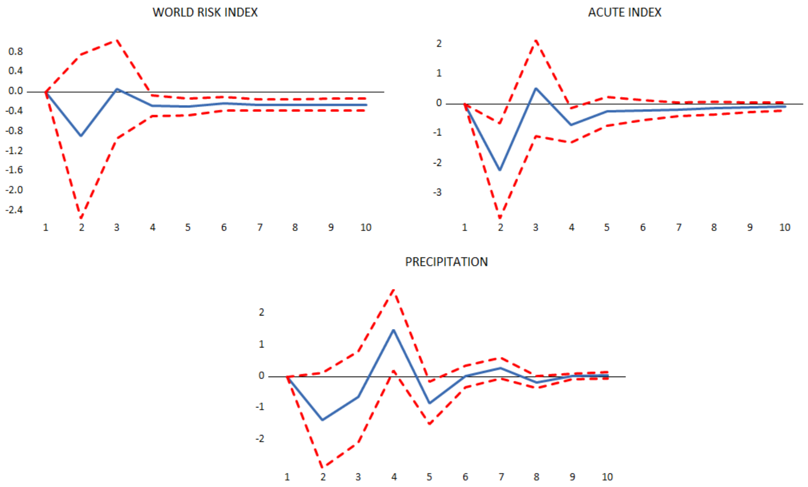
Notes: See the notes to Figure 1a. Precipitation refers to the year-on-year change in precipitation.

Figure 2a: IR of stock market returns to climate (transition) risk shocks – EU-28



Notes: The list of EU-28 countries is shown in Table 5. The blue line is the Impulse Response (IR), whilst the red dotted lines are the 95% confidence interval. Responses refer to Cholesky one standard deviation innovations. Standard errors are computed by means of 10,000 Monte Carlo simulations.

Figure 2b: IR of stock market returns to climate (physical) risk shocks – EU-28

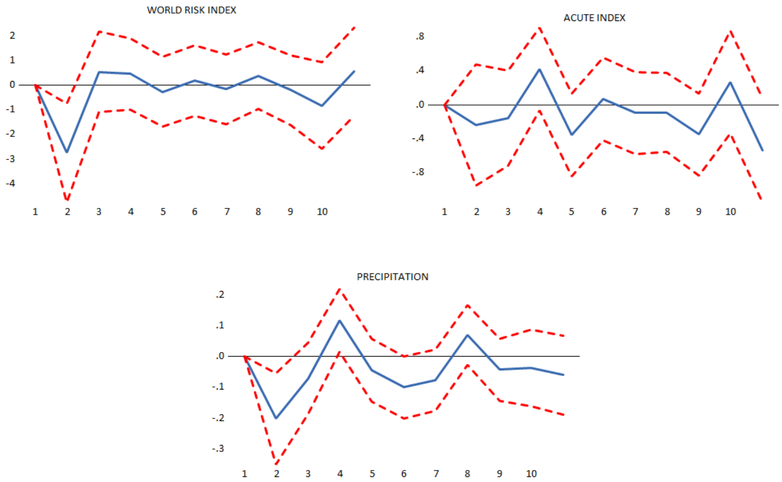


Notes: See the notes to Figure 2a.

Figure 3a: LP of stock market returns to climate (transition) risk shocks – Full sample

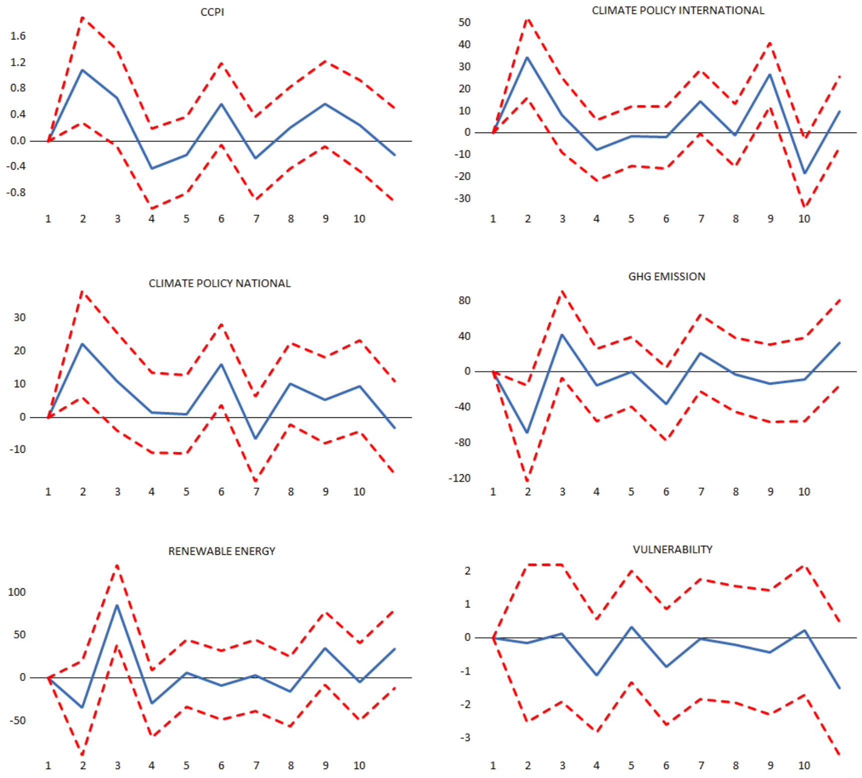
Notes: The blue line is the Local Projection (LP), whilst the red dotted lines are the 95% confidence intervals.

Figure 3b: LP of stock market returns to climate (physical) risk shocks – Full sample



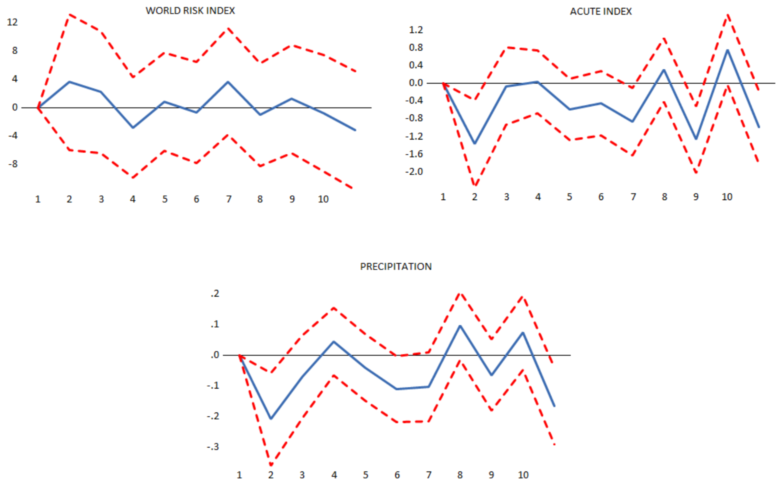
Notes: See the notes to Figure 3a.

Figure 4a: LP of stock market returns to climate (transition) risk shocks –EU-28



Notes: See the notes to Figure 3a.

Figure 4b: LP of stock market returns to climate (physical) risk shocks –EU-28



Notes: See the notes to Figure 3a.