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Abstract

Despite the increasing efforts to better understand the financial consequences of climate change, how climate-related financial risks could spill over across borders largely remain unexplored. This paper finds that climate transition risks could spill across borders by increasing the bilateral co-movement of stock market returns. The effect of climate transition risks increases with greater similarity of economic condition and larger dependence on import between two countries. On the other hand, good country performances in combating climate change can help to reduce the impact, but an effective mitigation likely requires good performances by both. Our results have three implications. First, evidence of stock market co-movement due to climate transition risks suggests international stock market investors may have to consider such spillover risks in their risk management practice. This necessitates continuous improvements in climate risk disclosures by corporates and financial institutions. Secondly, the cross-border spillover of climate transition risks is a global rather than a regional issue. A country with lower transition risks is not immune to the impact of climate change risks because of the potential for international spillover. Thirdly, our findings highlight a strong need for international efforts to deal with the risks of climate change to financial stability.

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1. Introduction

The Covid-19 pandemic has shown how vulnerable the global financial system is to non-financial shocks.[2] One such shock is climate change. At a broad level, climate change refers to changes in the Earth's condition, such as rising global temperatures, an increase in the frequency and severity of extreme weather events, among the many other effects (Brunetti et al, 2021). The threat of climate change to people's well-being is obvious, with more intense heat waves and hurricanes that have resulted in widespread death and destruction (United Nations Office for Disaster Risk Reduction, 2018), while rising sea levels have submerged many low-lying areas forcing millions of people to move to safer places (World Economic Forum, 2019).

Governments around the world have long been aware of these threats and devoted enormous efforts to combat climate change.[3] Financial regulators and international organisations have started to pay closer attention to climate-related risks and the implications for financial stability.[4] Risks to the financial system from climate change can be broadly classified into climate physical risks and transition risks. Climate physical risks refer to losses in financial assets and an increase in financial liabilities due to climate change-related extreme weather events, while climate transition risks refer to the changes in the value of financial assets and liabilities due to the adjustments towards a low-carbon country (FSB, 2020c).

Despite the increasing efforts to better understand the financial consequences of climate change, many issues remain largely unexplored, such as how climate-related financial risks can spill over across borders and give rise to financial stability issues. One way in which climate-related risk can spill across borders is via the co-movement in risk premia on assets exposed to climate-related risks in different jurisdictions (FSB, 2020c).[5] In particular, a disorderly transition towards a low-carbon country in one country might prompt expectations of a similar transition in another, providing a way for the climate transition risk in one country to spill over to others.

We consider the stock market as one important avenue for spillover risk. Apart from representing one of the largest asset classes, stock market investors have also put increasing emphasis on climate-related risks in their investment decisions (Choi et al, 2020; Shive and Forster, 2020 and Krueger et. al.,2020).[6] At the same time, many uncertainties remain on whether the risks are accurately assessed or adequately priced into stock returns (Liesen et al, 2017; Hong et al., 2019). Under these circumstances, an abrupt re-assessment or re-pricing of climate-related risks in one stock market could have a significant impact on the others. Such co-movement in stock market returns could have implications for financial stability.

Against this background, our study broadens the understanding of the climate transition risks spilling across borders through the stock market. Drawing on studies that found climate

[2] The Covid-19 pandemic has led to severe liquidity stress in the global financial system. A detailed review of the pandemic impact can be seen in FSB (2020b).

[3] The United Nations Climate Change Conference has been held annually since 1995 for UN members to assess progress in dealing with climate change. A number of important agreements on combating climate change have been struck at these conferences.

[4] For example, the Financial Stability Board (FSB) has published a series of reports on the financial stability issues related to climate change (FSB, 2020a, 2020c and 2021). It has also established the Task Force on Climate-related Financial Disclosures to develop a set of recommendations for reporting corporates' climate-related financial risks. The Network of Central Banks and Supervisors for Greening the Financial System (NGFS) was launched in 2017 to share best practices and contribute to the development of climate risk management in the financial sector.

[5] Another major channel is via the exposure of financial institutions, where financial institutions could withdraw financing to overseas entities due to a sharp rise in or re-assessment of climate-related risk exposures, leading to financing strains in these entities.

[6] Choi et al (2020) show that financial institutions have reduced their exposure to the stocks of high-emission industries since 2015. Shive and Forster (2020) reveal that there is a negative association between emissions and mutual fund ownership within public firms in the US. Krueger et. Al. (2020) find that institutional investors believe climate risks are already beginning to materialise in their portfolio holdings.

transition risks being priced into stock returns (e.g. Alessi et al., 2021; Bolton and Kacperczyk, 2021b) and the co-movement in stock markets internationally (e.g. Pretorius, 2002; Lucey and Zhang, 2010), this study examines the cross-border spillover of climate transition risks by empirically testing the relationship between climate transition risks and bilateral co-movement of stock market returns. In particular, we want to answer three research questions. First, whether there is a relationship between climate transition risk facing a stock market and its returns. The second question explores whether, and how, climate transition risks increase the bilateral co-movement of stock market returns. In particular, we explore the roles of various amplification factors. Recognising the importance of acting early on combating climate change, the final question studies whether good country performances in combating climate change could reduce the spillover of climate transition risks in stock markets.

Using a composite measure to assess the climate transition risks facing a stock market, this study has three findings. Firstly, we find a significant and positive relationship between climate transition risks facing a stock market and its subsequent returns. We interpret the results as evidence of a climate transition risk premium at the stock market level. Secondly, we further show that larger average climate transition risks in two stock markets are associated with a larger co-movement of their returns. This association increases with greater similarities in economic conditions and larger dependence on imports between two countries. Lastly, we find that effect of climate transition risks co-movement could be potentially reduced by good country performances in combating climate change, with the mitigation impact concentrated in countries with more similar economic condition. Applying the expectation hypothesis in FSB (2020c), one plausible explanation for this finding is that good climate change performance by a country may reduce the expectation on it to be subject to the same transition risks in another country. This may then reduce the co-movement of stock market returns due to climate transition risks.

This paper is organised as follows. The next section reviews the related literature. Section 3 discusses the empirical methodologies used to answer our research questions. Section 4 describes the data used. Section 5 discusses our empirical results, while the last section concludes.

2. Literature review

This study relates to two strands of literature. The first studies whether climate risks are priced into assets' returns. Some studies find that stock market investors demand a higher return from firms with higher climate risks. Focusing on the US stock market, Bolton and Kacperczyk (2021a) find evidence of a significant carbon risk premium for firms with higher total carbon dioxide emissions. Bolton and Kacperczyk (2021b) extend the study to over 14,400 firms in 77 markets and find a widespread carbon premium in all sectors across Asia, Europe and North America following the announcement of the Paris Agreement. Alesso et al (2021) also reveal that investors in the European markets accept lower returns to hold greener stocks. By constructing low carbon and carbon-intensive indices for the EU, US and global stock markets, Monasterolo and Angelis (2020) reveal that investors have demanded a higher risk premium for carbon-intensive assets also after the Paris Agreement. Gorgen et al. (2020) show that the "brown" firms are associated with a higher stock return when compared to "green" firms. In addition to the climate risks based on carbon emissions, Bansal et al (2019) show that long-run temperature fluctuations carry a positive risk premium in stock markets while Hsu et al (2021) show that investors may demand a higher return for a portfolio with high toxic emission intensity than others.

On the other hand, some studies show stocks with lower climate risks tend to be more resilient to unexpected shocks. For instance, Garel and Petit-Romec (2021) show that firms with responsible strategies on environmental issues experienced better stock returns during the Covid-19 shock. Ramelli et al (2021) reveal that firms with a higher carbon intensity experienced substantially negative abnormal returns around the timing of the first Global Climate Strike in 2019. Choi et al (2021) show that compared to firms with a lower carbon emission, stocks of carbon-intensive firms underperformed in abnormally warm weather. Engle et al. (2021) how a mimicking portfolio approach can be successful in hedging shock in climate change measured by news related to climate change. Taken together, these findings suggest that climate-related risks are becoming an important driver of stock market performance. More importantly, this implies that a sharp re-assessment or re-pricing of climate risk could induce stock market fluctuations and give rise to financial stability issues (FSB, 2020c and Hong et al., 2019).

For other asset classes, there is growing evidence that banks have started to price in climate risk in their lending to corporates. For instance, Ho and Wong (2021) reveal a higher loan spread is offered by banks if the firms have a higher carbon emission intensity in the Asia Pacific while Ehlers et al (2021) find similar results in 31 countries across the world. Evidence on the pricing of climate risk in property assets is mixed in comparison. Specifically, while Bernstein et al (2019) show that coastal homes vulnerable to sea-level rise are priced at a discount relative to similar homes at higher altitude, Baldauf et al (2020) find that greater flood risk due to sea level rise has little evidence of declining real estate prices. Murfin and Spiegel (2020) also find no evidence that sea level rise risk will impact residential real estate prices.

The second strand of literature relates to the determinants of the co-movement in international stock markets. Most studies measure the co-movement by the bilateral correlation of stock market returns.[7] Prior studies mostly focus on the role of economic or financial factors. For instance, Bracker and Koch (1999) find that divergent behaviour in several macroeconomic variables, including term structure and real interest rate, tends to be associated with lower return correlations in 10 national stock markets. Using a sample of 10 emerging stock markets, Pretorius (2002) reveals that stock markets in countries with larger industrial production growth differentials have a lower correlation while the correlation will be higher if two countries have a higher bilateral trade. Covering a sample of 40 national stock markets, Tavares (2009) shows that the correlation of returns increases with bilateral trade intensity, and decreases with the real exchange rate volatility, output growth dissimilarity and export dissimilarity. Dutt and Mihov (2013) find that the correlation of stock market returns increases with similarity in industry structure over 58 national stock markets. Although climate risk has emerged as one significant driver of stock market performance, whether it will be one determinant of stock market co-movement is yet to be examined.

In summary, the first strand of literature shows that stock market investors have started to price climate risks into stock returns, but potential systematic impacts of such development largely remain unexplored. The second mainly discusses the roles of macroeconomic and financial factors in the co-movement in international stock markets, but not so much for non-economic or financial factors, especially for climate risks.[8] Our study contributes to the literature by exploring the role of climate transition risks in the co-movements of international stock markets.

[7] On the other hand, Bracker et al (1999), Johnson and Soenen (2002) and Johnson and Soenen (2003) use Geweke (1982) measure of feedback as a proxy for stock market co-movements.

[8] Flavin et al (2002) and Pretorius (2002) study the role of geographical factors while Lucey and Zhang (2010) study the role of cultural factors. Yet, to our best knowledge, there are no prior studies that cover the role of climate risks.

3. Empirical Methodology

This section introduces the empirical models to answer our three questions.

3.1 It there a relationship between climate transition risk and stock market returns?

Referencing Bolton and Kacperczyk (2021a and 2021b), we consider a characteristics-based model as follows;

$$r_{i,t} = \alpha + \beta_{CR} CR_{i,t-1} + \sum_{k=1}^{K} \beta_k Control_{i,t-1}^{k} + \beta_{vix} vix_t + GFC_t + COVID_t + \epsilon_i + \varepsilon_{i,t} \quad (1)$$

In the above model, $r_{i,t}$ refers to the annualised daily stock market return of country i at year t. It is calculated as the average daily percentage in the representative stock market index of country i before multiplied by 250 days. All stock market indices are converted to US dollars which facilitate cross-market comparison.

$CR_{i,t-1}$ is a composite measure of climate transition risk facing a country and its stock market at time *t-1*. Specifically, it is constructed by applying principal component analysis on five climate-related indicators, namely i) CO_2 emission per capita, ii) energy consumption per capita, iii) share of primary energy generated from non-renewable sources, iv) CO_2 per unit energy generation and v) aggregate ratio of Scope 1 and 2 CO_2 emission to total revenue for domestic listed companies in country i. The first four indicators resemble the key components of country's climate transition risk score considered by the European Investment Bank (2021), which reflects the future decarbonisation required by each country and, therefore, the associated risks of such transition. Apart from the overall climate transition risk in the country when the stock market is located, the risk facing the stock market also depends on the risk exposure of underlying listed companies. Therefore, the composite measure also includes the aggregate Scope 1 and 2 CO_2 emission of domestic listed companies. The principal component is chosen such that all indicators are positively correlated, with a larger value denoting larger climate transition risks.[9]

The regression coefficient β_{CR} captures the relationship between climate transition risks and stock market returns. Firm-level studies by Bolton and Kacperczyk (2021a and 2021b) show that investors will require a higher return for firms exposed to higher climate (carbon) transition risks. We argue that the same reason also explains the higher aggregate returns in a stock market due to higher climate transition risks. Therefore, we expect β_{CR} to be positive.

The model also controls for other stock market or country-level factors that are found to affect stock market returns (Santis and Gerard, 1997; Ferson and Harvey, 1998; Gompers and Metrick, 2001). Specifically, $Control_{i,t-1}^{k}$ is a vector of variables for country i, covering key economic indicators including real GDP growth rate ($gdpg_i$), inflation rate ($infl_i$), term spread (ts_i), and real interest rate ($rint_i$). As all stock market indices are denominated in USD, we also include the exchange rate changes (against the USD) to control for exchange rate movements ($fxchange_i^{USD}$). Several stock market indicators including size ($size_i$), dividend yield ($divy_i$) and book to market value ratio (bm_i) are also included.[10] At the global level, the VIX index (denoted by vix_t) is used to control the global financial condition at time t. The model additionally controls for the market anomalies during the 2008 – 09 Global Financial Crisis

[9] The second principal component, which satisfies the correlation requirement, is chosen in this regard.

[10] All stock market / country-level variables, including $CR_{i,t-1}$, enter in lag term to avoid the reverse causality issue. This also allows us to interpret the model coefficients as the impact of different explanatory variables on the expected stock market return (assuming perfect foresight).

(GFC) and 2020 COVID-19 pandemic.[11] Finally, ϵ_i denotes country-fixed effects and $\varepsilon_{i,t}$ represents the error term. The definition of each variable can be found in Annex A, while Section 4 discusses the data in more detail.

3.2 Whether and how does climate transition risk increase the bilateral co-movement of stock markets' returns?

Answering this question requires a measure of the bilateral co-movement of stock market returns for a given country pair i and j (denoted by $Comove_{ij,t}$). We use the unconditional correlation of daily stock market returns as our baseline co-movement measure, as it is easier to interpret than other potential measures. This measure is also widely used in literature. As such, $Comove_{ij,t}$ is given by the following formula;

$$Comove_{ij,t} = \frac{\sum_{t\epsilon \mathrm{T}}\left(r_t^i-\bar{r}^i\right)\left(r_t^j-\bar{r}^j\right)}{\sqrt{\sum_{t\epsilon \mathrm{T}}\left(r_t^i-\bar{r}^i\right)^2}\sqrt{\sum_{t\epsilon \mathrm{T}}\left(r_t^j-\bar{r}^j\right)^2}} *100 \quad (2)$$

r_t^i and r_t^j is daily stock market return of country i and j at period $t\epsilon\mathrm{T} = \{1, \ldots, T\}$ respectively. $\bar{r}^i$ and $\bar{r}^j$ is the sample mean of r^i and r^j across the period t. An increase in $corr\left(r_t^i, r_t^j\right)$ denotes a higher degree of co-movement between the stock market returns of country i and j. The measure is multiplied by 100 such that the co-movement is represented in percentage point form.

With $Comove_{ij,t}$ we investigate its relationship with climate transition risks using the following panel regression model;

$$Comove_{ij,t} = \alpha + \beta_{CR} CR_{ij,t-1} + \sum_{k=1}^{K} \beta_k Control_{ij,t-1}^k + \beta_{VIX} vix_t + GFC_t + COVID_t + \epsilon_{ij} + \varepsilon_{ij,t} \quad (3)$$

In the above equation, $CR_{ij,t-1}$ measures the average climate transition risks in country i and j. Analogous to $CR_{i,t-1}$ Equation 1, it is constructed as the principal component of the average values of i) CO_2 emission per capita, ii) energy consumption per capita, iii) share of primary energy generated from non-renewable sources, iv) CO_2 per unit energy generation and v) aggregate ratio of Scope 1 and 2 CO_2 emission to total revenue for domestic listed companies of stock market i and j. Under this set-up, the relationship between climate transition risks (i.e., $CR_{ij,t-1}$) and bilateral co-movement of stock market returns (i.e., $Comove_{ij,t}$) is captured by regression coefficients β_{CR}.

To avoid omitted variable bias and to better identify the effect of climate transition risks, the model includes some commonly used determinants of bilateral co-movement of stock market returns. They include i) similarity in economic condition, ii) differences in stock market sizes, iii) volatility in bilateral exchange rates, as well as iv) export and v) import dependence. Similar to Equation 1, the model also controls for global market condition with vix , especially as stock markets tend to exhibit a stronger co-movement under market stress (ECB, 2008). Same as Equation 1, Equation 3 also controls the market anomalies during the 2008 – 09 GFC and 2020 COVID-19 pandemic. Elsewhere, stock market-pair fixed effects (ϵ_{ij}) are included to control for time-invariant stock market-pair characteristics. The definition of each variable can be found

[11] This is achieved by adding additional time dummy variables for the two mentioned periods as shown in Equation 1 (GFC and $COVID$).

in Annex A. Finally, to avoid the results being biased by stock market pairs of inactive trading activities, we follow Lucey and Zhang (2010) and exclude the thin-trading market pairs from the analysis.[12]

To further identify factors that may amplify the effect of climate transition risk, we consider an extended model in Equation 4 below;

$$Comove_{ij,t} = \alpha + \beta_{CR} CR_{ij,t-1} + \beta_{Fac} CR_{ij,t-1} \times Factor_{ij.t-1} + \sum_{k=1}^{K} \beta_k Control_{ij,t-1}^{k} + \beta_{VIX} vix_t + GFC + COVID + \epsilon_{ij} + \varepsilon_{ij,t} \quad (4)$$

Compared to Equation 3, in Equation 4 we include an interaction term $CR_{ij,t-1} \times Factor_{ij.t-1}$, which captures how the relationship between $CR_{ij,t-1}$ and $Comove_{ij,t}$ varies with the magnitude of $Factor_{ij.t-1}$. A total of four factors are considered.[13] The first three factors are similarity in economic condition, geographical distance and differences in stock market sizes. These three factors are based on FSB (2020c), which suggests that the market's expectations on climate policies in one country (and therefore the potential climate transition risks) is dependent on the policies in the other. Accordingly, Equation 4 tests whether such dependence would be stronger when the two stock markets have smaller differences in these three aspects. The last factor covers the import dependence between two countries. Our climate transition risk measure mainly reflects the risk arising from domestic emissions, while a country could be subject to the climate transition risk in another through goods import when the carbon tax is priced in the imported goods. Meanwhile, Ben-David et al. (2021) documents multinational corporations could "export" carbon emissions to a "host" country with less stringent environmental regulations. In return, these corporations could be exposed to climate transition risks in the "host" country through importing goods (e.g. intermediation goods for further production process) from there.

3.3 Does a better performance in combating climate change reduce the impact of climate transition risks?

We wrap up the analysis by investigating whether better countries' performance in combating climate change (referred to as "climate change performance" hereafter) could reduce the impact of climate transition risks. While the indicators used to construct $CR_{ij,t-1}$ allow us to measure current risk exposure to the stock markets, they do not take into account countries' performance in combating climate change. A better climate change performance by a country would reduce the expectation on it being subject to the transition risks happening in another. This could reduce the potential spillover of climate transition risks from one stock market to another, reflected by a smaller impact of $CR_{ij,t-1}$ on $Comove_{ij,t}$.

To test this hypothesis, we replace $Factor_{ij.t-1}$ in Equation 4 by countries' average performance in combating climate change, denoted by $Performance_{ij,t-1}$.

$$Comove_{ij,t} = \alpha + \beta_{CR} CR_{ij,t-1} + \beta_{Per} CR_{ij,t-1} \times Performance_{ij,t-1} + \beta_{Peri} Performance_{ij,t-1} + \sum_{k=1}^{K} \beta_k Control_{ij,t-1}^{k} + \beta_{VIX} vix_t + GFC + COVID + \epsilon_{ij} + \varepsilon_{ij,t} \quad (5)$$

[12] At each year, a certain stock market pair is excluded from the estimation sample when the annual turnover (as % of GDP) rank below one-third of all sample markets for both markets. Our results largely hold when such restriction is relaxed. Results are not reported for brevity.

[13] Annex B discusses their roles in more detail.

A country's climate performance is captured by the annual climate change performance index (CCPI) published jointly by Germanwatch, CAN International and the NewClimate Institute. CCPI tracks countries' efforts to combat climate change in four aspects, namely i) GHG emission reduction, ii) adoption of renewable energy, iii) energy efficiency and iv) adoption of climate policies. In each year, countries are assessed and assigned a score that reflects their performance (in each of the four aspects) relative to the others during the year. The CCPI, which reflects the overall relative performance, is calculated by the summation of four scores. The countries will be further sorted by their CCPI and classified into 5 ratings, ranging from very low, low, medium, high to very high performance. For each of the countries pair i and j, we calculate their average rating in year *t-1* as $Performance_{ij,t-1}$ in Equation 5.[14,15]

The coefficient of interest in Equation 5 is β_{Per}. This represents the differences in the association between $CR_{ij,t-1}$ and $Comove_{ij,t}$ due to variations in $Performance_{ij,t-1}$. We expect β_{Per} to be negative as we hypothesise a better performance in combating climate change could reduce the impact of climate transition risks.

4 **Data**

We follow studies by Lucey and Zhang (2010), Dutt and Mihov (2013), Johnson and Soenen (2003) to apply the MSCI equity market indices as the representative stock market index for our sample countries. Weighted by market capitalisation of constituent stocks, these indices are designed to measure the performance of the larger and mid cap segment in the stock market of respective countries. These indices are compiled with the same methodology to enhance comparability of the indices (and the stock market returns) across countries. In addition, the representativeness of all these indices is assessed to be adequate as they cover approximately 85% of the stock universe in respective countries.

Chart 1 depicts the box plots of annualised daily stock market returns by year. Three observations emerge. First, there are rich variations in stock market returns which would facilitate the identification of relationships between stock market returns and climate transition risk. Secondly, the box plots show a strong cyclical movement which is closely related to the movement in the global market volatility (represented by the vix, red line in Chart 1). This justifies our model specifications that include the VIX index as a control variable. Thirdly, noticeable outliers (black dots in Chart 1) are observed in different years, therefore, we winsorise the observations of stock market return at 2.5% and 97.5%, such that our results are not unduly influenced by the outliers.[16]

For indicators used to construct the climate transition risk measure, countries' CO_2 emission per capita, CO_2 per unit energy, share of primary energy from non-renewable source and energy consumption per capita (the proxy for climate transition risks) are sourced from the Carbon and Greenhouse Gas Emissions dataset maintained by Our World in Data[17], while aggregate ratio of Scope 1 and 2 CO_2 emission to total revenue for domestic listed companies are derived using firm-level data from Trucost and Capital IQ. Upper panel of Chart 2 shows that the median

[14] We first assign integer values to each of the five ratings, from 1 (very low) to 5 (very high) before calculating their average rating.

[15] We opt for the rating instead of actual CCPI as the calculation of CCPI scores change across years, such that the absolute level of score is not comparable across years. Regarding this, converting them into relative scores will still be needed.

[16] In empirical estimations we also winsorise the explanatory variables with extreme outliers at 2.5% and 97.5% respectively.

[17] It covers the annual data of at country level back to the eighteenth century.

values of all five indicators were generally on a declining trend between 2003 and 2019. Accordingly, the median value of climate transition risk measure also displays a declining trend over time (lower panel of Chart 2).

Table 1 presents the summary statistics of stock market returns, the five indicators used in the climate transition risks measure and other control variables included in Equation 1. Taking into account the data availability of these variables, our final estimation sample for Equation 1 includes 43 countries and covers the annual observations from 2004 to 2020.[18]

Left panel of Chart 3 depicts the average bilateral stock market co-movement (Equation 2) between 2004 and 2020. The average co-movement of all country-pairs (i.e. red line) rose noticeably in 2008 (Global Financial Crisis) and 2020 (Covid-19 pandemic). This aligns with ECB (2008) where stock market co-movements tend to heighten in times of extreme market volatility (a reflection of market contagion). It points to the importance of, and appropriateness to, control for global market volatility when we study the relationships between climate transition risks and the bilateral co-movement of stock market returns in Equation 3. Meanwhile, right panel of Chart 3 illustrates noticeable differences in the average bilateral co-movement between two AEs and two EMEs. This highlights the need to control for structural differences across stock market pairs (which may not vary over time) via the stock market-pair fixed effects (i.e. ϵ_{ij}) in Equation 3.

Table 2 reports the variables used in Equation 3 while Table 3 reports the correlation matrix of these variables. The first column of Table 3 displays the Pearson correlation coefficients between the co-movement measure and different explanatory variables. As our variable of interest, the co-movement measure is positively correlated with the climate transition risk measure. Meanwhile, the correlations between co-movement measure and the control variables are in line with literature. For instance, the co-movement is positively related to the similarity in economic conditions, and negatively related to differences in stock market. The co-movement measure also increases with import and export dependence, as well as VIX index Elsewhere, we do not notice substantial correlation between most explanatory variables, suggesting low risks of collinearity issues. That said, we do observe very strong correlation between import and export dependence at 0.91. Therefore, we will first remove the effect of export dependence from the import dependence variable such that we can accommodate both variables in Equation 3.[19]

5. Empirical results and discussion

5.1 Is there a relationship between climate transition risk and stock market returns?

Table 4 reports the estimation results of Equation 1. Focusing on the annual sample period from 2004 to 2020, Table 4 shows the estimated β_{CR} is positive and statistically significant. A higher climate transition risk facing a stock market in a particular year is associated with a higher return next year. Similar to Bolton et al. (2021b), we interpret the positive relationship as a form of climate transition risk premium in stock market.[20] The significant relationship between

[18] Annex C lists the 43 countries in our data sample.

[19] This is achieved by taking the residuals from regressing import dependence on export dependence. Such treatment also helps to remove effect of export dependence when we study the role of import dependence in Equation 4.

[20] The signs of the estimated coefficients of the control variables are in line with what literature found. For instance, the negative coefficient between real GDP growth rate and returns is consistent with the likes of Ritter (2005) and MSCI (2010). Ritter (2005) argues that the relationship could be negative in the sense that since long-run stock returns depend on dividend yields as well as its growth, while economic growth was mainly driven by new firms by technological advancement, which might not necessary raise the growth rate of dividends per share for existing firm.

climate transition risk and stock market return found provides a basis for our subsequent analysis on the relationship between climate transition risk and co-movement of stock market returns.

5.2 Whether and how climate transition risks increase the bilateral co-movement of stock markets' returns?

We find a positive relationship between climate transition risk and bilateral co-movement of stock market returns. Specifically, Panel a of Table 5 reports the estimation results of Equation 3, where the first column shows that the estimated β_{CR} is positive and statistically significant. A higher average transition risk in two stock markets is associated with a larger co-movement of their returns, holding other things constant.

By separating β_{CR} before and after the announcement of the Paris Agreement, Column 2 shows that the estimated β_{CR} is more positive after the announcement of the Paris Agreement. Such results may reflect a larger awareness by stock market investors on the interconnections between stock markets due to climate transition risks.

To further explore factors driving the positive relationship reported in Table 5, we estimated Equation 4 and the results are reported in Panel b of Table 5. By looking at the estimated β_{Fac} (see row $CR_{ij,t-1} \times Factor_{ij,t-1}$), our estimation results show that the positive effect of climate transition risk would increase with larger similarity in economic conditions (Column 1) and stronger import dependence between two countries (Column 4). Geographical distance and differences in stock markets' sizes, on the other hand, do not impose any significant differences in the relationship (Column 2 and 3). Overall, the significance of the two amplification factors identified suggest climate transition risks could spill through stock markets via countries' economic linkages.

5.3 Does a better performance by countries in combating climate change reduce the spillover of climate transition risks?

Column 1 of Table 6 reports the estimation results of Equation 5. Specifically, the estimated β_{Per} is negative and statistically significant (see row $CR_{ij,t-1} \times Performance_{ij,t-1}$), suggesting the effect of climate transition risk is smaller when the two countries display better climate change performance on average.

To link the above finding with the expectation hypothesis on climate transition risk spillover, we conducted additional analysis by separately estimating Equation 5 on two sub-samples of stock market pairs with large and small similarities in economic condition, a significant amplification factor in Table 5 based on the "expectation" hypothesis.

Column 2 to 3 of Table 6 report the results. In particular, the results show that the estimated β_{Per} is only significantly negative in the sub-sample of stock market pairs with large similarity in economic condition (Column 2). This provides supports to our conjecture that the climate change performance reduces the spillover effect by lowering the expectation of the transition risk facing one market to replicate in another.

We also find the importance of mutual efforts in combating climate change. Specifically, we consider a revised model that separate the estimated β_{CR} into three cases, specifically i) both countries showing good climate change performance, ii) just one country showing good climate change performance, and iii) neither of them demonstrate good performance.[21] The estimated

[21] Specifically, we consider the equation as follow;

results are reported in Column 4, showing that estimated β_{CR} could become smaller (less positive) when only one country has good climate change performance (see row $CR_{ij,t-1} * D^{Sing}_{ij,t-1}$, with an estimated coefficient of -1.4). The reduction in estimated β_{CR} would be more than doubled when both countries have good climate change performance (see row $CR_{ij,t-1} * D^{Sing}_{ij,t-1}$, with an estimated coefficient of -3.65). The results suggest the relevance of countries' mutual efforts in addressing the impact of climate change on financial stability.

6. Conclusion and implications

This study broadens the understanding of the cross-border spillover of climate transition risks by examining whether, and how, climate transition risks increase the bilateral co-movement of stock market returns. Specifically, we first establish a broad–based relationship between climate transition risk and stock market returns. We further show that larger climate transition risks are associated with larger bilateral co-movement of stock market returns. The association increases with similarity in economic conditions and import dependence between two countries. Finally, while a good performance in combating climate change can help to lessen the impact, an effective mitigation likely requires a good performance by both countries.

Our findings have three implications. First, the impact of climate transition risks on co-movement of stock market returns suggests climate transition risks in one market could have a spillover effect on the others. International stock market investors may therefore have to take into account the potential spillover risks in their risk management practices. To this end, a sound management of climate transition risk spillover necessitates continuous improvements in climate risks disclosures by corporates and financial institutions. Secondly, a stock market facing low transition risks itself is not immune to the impact of climate change because of the potential for international spillover. On this, our study broadens the understanding of factors that may amplify the risks spillover. Thirdly, our findings highlight a strong need for international efforts and early actions to deal with the impact of climate change on financial stability.

Finally, we wish to highlight two limitations of this study which may provide directions for future research. First, we focus on climate transition risks due to better data availability. A better understanding on the spillover of physical risks is also necessary to develop a more complete picture on the impacts of climate change on financial stability. Second, this study focuses only on stock markets given the more-established literature on their inter-connection and potential drivers of spillover risks. The spillover risks in other asset classes, such as bonds and commodities, will also require better understanding and we leave that to future research.

$$Comove_{ij,t} = \alpha + \beta_{CR}CR_{ij,t-1} + \beta_{Both}CR_{ij,t-1} * D^{Both}_{ij,t-1} + \beta_{Sing}CR_{ij,t-1} * D^{Sing}_{ij,t-1} + D^{Both}_{ij,t-1} + D^{Sing}_{ij,t-1} + \sum_{k=1}^{K} \beta_k Control^{k}_{ij,t-1} + \beta_{VIX}vix_t + GFC_t + COVID_t + \epsilon_{ij} + \varepsilon_{ij,t}$$

$D^{Both}_{ij,t-1}$ and $D^{Sing}_{ij,t-1}$ are two dummy variables when both countries i and j display good climate change performance and exactly one of them displaying good climate change performance respectively. A country is defined as having good climate change performance when its CCPI rating is equal to or above "medium". In this set-up, β_{Both} (β_{Sing}) captures the reduction in the effect of climate transition risks when two (one) countries have good climate change performance.

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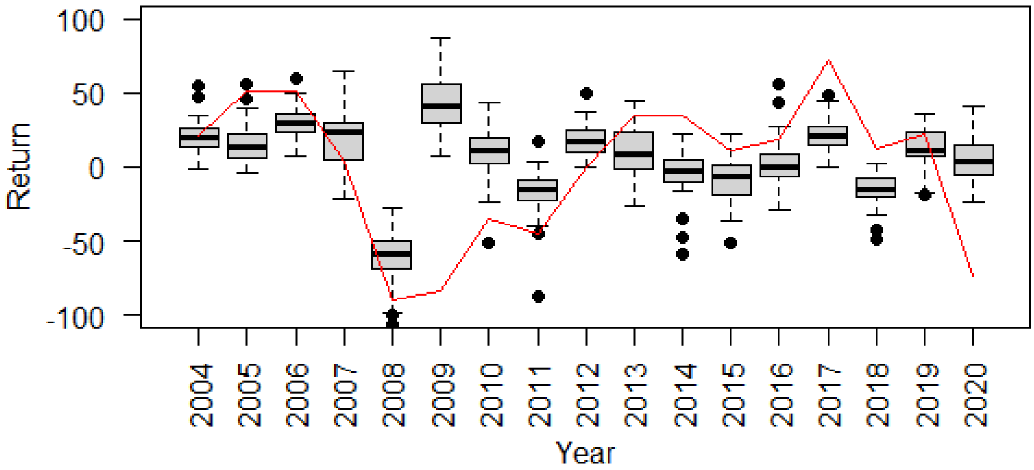
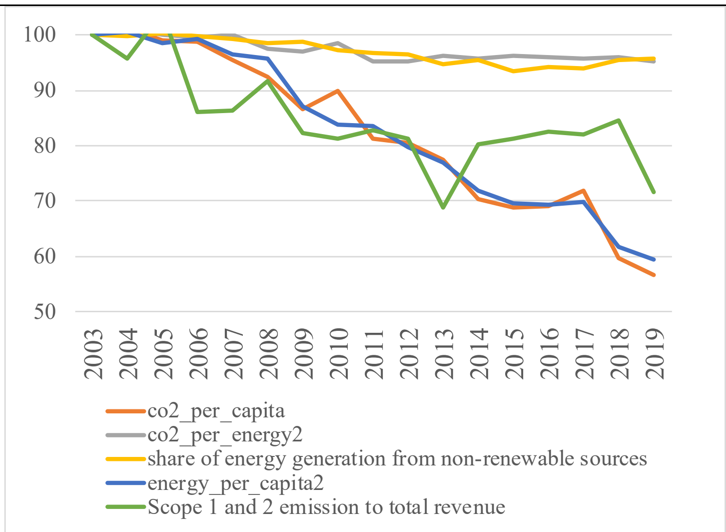
Chart 1: Distributions of stock market returns over time



Note: The VIX Index (red line, in logarithm form) is re-scaled such that a higher value denotes a lower volatility.

Chart 2: Stock markets' climate transition risks over time

(a) Raw climate risk indicators

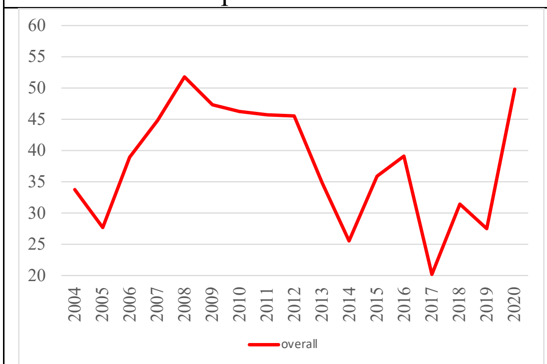


(b) Composite climate transtion risk measure

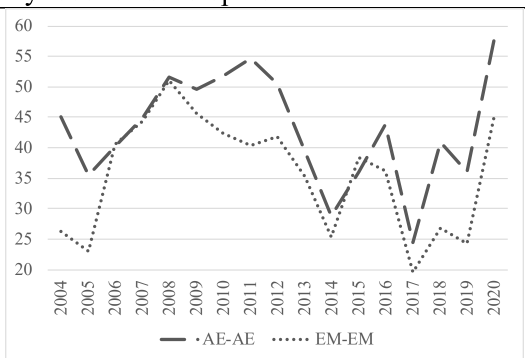
Note: All indicators in the upper panel are normalised with values in 2003 equal 100. The lower panel depicts the second principal component of five raw indicators (chosen such that all five raw indicators are positively correlated with the composite measure.

Chart 3: Average bilateral co-movement of stock markets returns over time

All stock market pairs



By level of development



Note: The bilateral co-movement of stock market returns is calculated using Equation 2

Table 1: Summary statistics of regression variables in Equation 1

The annual sample period is 2004 – 2020. $r_{i,t}$ refers to the annualized daily stock market return of country i in year t. $co2/capita_{i,t-1}$, $co2/energy_{i,t-1}$, $energy/capita_{i,t-1}$,$non-renew_{i,t-1}$ and refer to CO_2 emission per capita, CO_2 per unit energy generation, energy consumption per capita, share of primary generation from non-renewable sources in country i respectively. $Scope$ 1 & 2 / $TR_{i,t-1}$ refers to aggregate ratio of Scope 1 and 2 CO_2 emission to total revenue of domestic listed companies in stock market i. $size_{i,t-1}$, $bm_{i,t-1}$ and $divy_{i,t-1}$ stand for size, book-to-market ratio and dividend yield respectively. $infl_{i,t-1}$, $gdpg_{i,t-1}$,$ts_{i,t-1}$, $rint_{i,t-1}$ and$fxchange^{USD}_{i,t-1}$ refer to inflation rate, growth rate of real GDP, term spread, real interest rate and exchange rate movement with respect to USD. The VIX index (in logarithm and multiplied by 100) is denoted by vix_t.

	No. of observations	Mean	Standard deviation	Min	Max	Skewness
$r_{i,t}$	577	5.73	25.80	-7.43	22.89	-0.62
$co2/capita_{i,t-1}$	577	7.80	4.40	4.65	10.05	0.64
$co2/energy_{i,t-1}$	577	0.20	0.06	0.17	0.23	-0.27
$energy/capita_{i,t-1}$	577	43723	30028	23759	56253	1.56
$non-renew_{i,t-1}$	577	87.40	11.30	81.94	95.59	-1.06
$Scope$ 1 & 2 / $TR_{i,t-1}$	577	502.16	427.45	246.89	570.52	2.09
$CR_{i,t-1}$	577	0.00	1.28	-0.91	0.90	-0.17
$size_{i,t-1}$	577	112.70	359.31	21.97	71.91	5.82
$bm_{i,t-1}$	577	0.58	0.23	0.41	0.70	1.29
$divy_{i,t-1}$	577	3.08	1.31	2.15	3.83	1.06
$infl_{i,t-1}$	577	2.72	2.98	1.02	3.52	2.88
$gdpg_{i,t-1}$	577	2.15	3.04	0.64	3.69	0.61
$ts_{i,t-1}$	577	0.26	15.44	0.46	1.65	-19.80
$rint_{i,t-1}$	577	2.78	5.60	0.11	3.76	4.19
$fxchange^{USD}_{i,t-1}$	577	0.00	0.10	-0.06	0.07	-0.27
vix_t	577	287.78	31.40	240.61	348.71	0.64

Table 2: Summary statistics of regression variables in Equation 3

$Comove_{ij,t}$ denotes the unconditional correlation between daily stock market returns of two country i and j in year t (Equation 2). $co2/capita_{ij,t-1}$, $co2/energy_{ij,t-1}$, $energy/capita_{ij,t-1}$,$non-renew_{ij,t-1}$ and refer to average CO_2 emission per capita, CO_2 per unit energy generation, energy consumption per capita, share of primary generation from non-renewable sources in country i and j respectively. $Scope\ 1\ \&\ 2\ /\ TR_{ij,t-1}$ refers to average aggregate ratio of Scope 1 and 2 CO_2 emission to total revenue of domestic listed companies in stock market i and j. $Sim^{Econ}_{ij,t-1}$ refers to the first principal component of absolute differences in real GDP growth, real interest rate, inflation rate and term spreads, and converted such that a larger $Sim^{Econ}_{ij,t-1}$ denotes larger differences in all four indicators. $Dist_{ij}$refers to the geographical distance between the capital cities of countries i and j. $Sizediff_{ij,t-1}$refers to the absolute differences in stock market size (as % of GDP). $import_{ij,t-1}$ stands for the average of the ratio of country i import from country j to total import of country i and the ratio of country j import from country i to total import of country j. $export_{ij,t-1}$ stands for the average of the ratio of country i export to country j to total export of country i and the ratio of country j export to country i to total export of country j. $fxchange\_sd_{ij,t-1}$ refers to the annualized standard deviation of the daily percentage change of bilateral exchange rate. The VIX index (in logarithm and multiplied by 100) is denoted by vix_t. The annual sample covers 2004 to 2020 and excludes thin-trading stock market pairs (annual turnover rank below one-third of all sample markets for both markets).

	No. of observations	Mean	Standard deviation	Min	Max	Skewness
$Comove_{ij,t}$	4087	38.62	18.79	-8.52	75.59	-0.02
$co2/capita_{ij,t-1}$	4087	7.53	3.38	5.42	10.04	0.48
$co2/energy_{ij,t-1}$	4087	0.21	0.04	0.18	0.23	-0.15
$energy\ /capita_{ij,t-1}$	4087	39048	23361	27350	54589	1.05
$non-renew_{ij,t-1}$	4087	89.41	8.21	82.13	94.74	-0.68
$Scope\ 1\ \&\ 2\ /\ TR_{ij,t-1}$	4087	448.03	280.18	323.71	667.74	2.27
$CR_{ij,t-1}$	4087	0.00	1.21	-3.93	3.32	-0.32
$Sim^{Econ}_{ij,t-1}$	4087	0.00	1.29	-11.64	1.39	-4.74
$Dist_{ij}$	324	8.82	0.80	6.25	9.88	-1.21
$Sizediff_{ij,t-1}$	4087	64.77	84.74	0.04	517.53	2.74
$import_{ij,t-1}$	4087	5.48	8.63	0.02	78.84	3.61
$export_{ij,t-1}$	4087	5.41	10.04	0.03	110.07	5.49
$fxchange\_sd_{ij,t-1}$	4087	0.11	0.05	0.00	0.28	1.03
vix_t	17	287.78	31.40	240.61	348.71	0.64

Table 3: Correlation matrix of regression variables in Equation 3

This table reports the Pearson correlation coefficients between the co-movement measure and different explanatory variables in Equation 3. $Comove_{ij,t}$ denotes the unconditional correlation between daily stock market returns of two country i and j in year t (Equation 2). $CR_{ij,t-1}$ refers to the average climate transition risks of country i and j, measured by the average principal component of five climate transition risk related indicators as outlined in Section 3.2. $Sim_{ij,t-1}^{Econ}$ refers to the first principal component of absolute differences in real GDP growth, real interest rate, inflation rate and term spreads, and converted such that a larger $Sim_{ij,t-1}^{Econ}$ represents smaller differences in all four indicators. $Dist_{ij}$ refers to the geographical distance between the capital cities of countries i and j. $Sizediff_{ij,t-1}$ refers to the absolute differences in stock market size (as % of GDP). $import_{ij,t-1}$ stands for the average of the ratio of country i import from country j to total import of country i and the ratio of country j import from country i to total import of country j. $export_{ij,t-1}$ stands for the average of the ratio of country i export to country j to total export of country i and the ratio of country j export to country i to total export of country j. $fxchange\_sd_{ij,t-1}$ refers to annualized standard deviation of daily percentage change of bilateral exchange rate. The VIX index (in logarithm) is denoted by vix_t. The annual sample covers 2004 to 2020 and excludes thin-trading stock market pairs (annual turnover rank below one-third of all sample markets for both markets).

	$Comove_{ij,t}$	$CR_{ij,t-1}$	$Sim_{ij,t-1}^{Econ}$	$Dist_{ij}$	$Sizediff_{ij,t-1}$	$import_{ij,t-1}$	$export_{ij,t-1}$	$fxchange\_sd_{ij,t-1}$	vix_t
$Comove_{ij,t}$	1.00								
$CR_{ij,t-1}$	0.06	1.00							
$Sim_{ij,t-1}^{Econ}$	0.11	-0.02	1.00						
$Dist_{ij}$	-0.33	-0.06	0.03	1.00					
$Sizediff_{ij,t-1}$	-0.21	-0.15	0.01	-0.05	1.00				
$import_{ij,t-1}$	0.22	0.17	0.06	-0.45	-0.06	1.00			
$export_{ij,t-1}$	0.19	0.17	0.07	-0.39	0.00	0.92	1.00		
$fxchange\_sd_{ij,t-1}$	-0.04	-0.07	-0.14	0.25	-0.03	-0.19	-0.18	1.00	
vix_t	0.43	-0.01	0.00	0.02	-0.04	-0.01	-0.02	0.16	1.00

Table 4: Estimated relationship between climate transition risks and stock market returns

This table reports the estimation results of Equation 1. The dependent variable $r_{i,t}$ stands for the annualized stock return of country i in year t. CR_i refers to the climate transition risks of country i, measured by the principal component of five climate transition risk related indicators as outlined in Section 3.1. $size_i$, bm_i and $divy_i$ stand for stock market size, book-to-market ratio and dividend yield respectively. $infl_i$, $gdpg_i$, ts_i, $rint_i$ and $fxchange_i^{USD}$ refer to inflation rate, growth rate of real GDP, term spread, real interest rate and exchange rate movement with respect to USD. vix_t denotes the VIX index (in logarithm and multiplied by 100). Except CR_i and vix, all continuous variables are winsorised at 2.5% and 97.5% before estimation. ***, ** and * represent 1%, 5% and 10% significance level respectively. Robust standard errors are presented at the parentheses. The annual sample period covers 2004 to 2020.

	Dependent variable: $r_{i,t}$
$CR_{i,t-1}$	**0.09*** **
	(0.03)
$size_{i,t-1}$	-0.09
	(0.06)
$bm_{i,t-1}$	**-0.20*** **
	(0.08)
$divy_{i,t-1}$	**2.14** **
	(1.04)
$infl_{i,t-1}$	**3.60*** **
	(0.89)
$gdpg_{i,t-1}$	**-1.57*** **
	(0.49)
$ts_{i,t-1}$	**4.35*** **
	(1.09)
$rint_{i,t-1}$	0.34
	(0.59)
$fxchange_{i,t-1}^{USD}$	**-0.73*** **
	(0.09)
vix_t	**-0.41*** **
	(0.05)
Observations	577
Number of countries	43
GFC control	Yes
COVID control	Yes
Stock market / Country-fixed effects	Yes
R^2	0.32
Adjusted R^2	0.27

Table 5: Estimated relationship between climate transition risk and bilateral co-movement of stock market returns

This table reports the estimation results of Equation 3 (panel a) and 4 (panel b). $Comove_{ij,t}$ denotes the unconditional correlation between daily stock market returns of two country i and j in year t (Equation 2). CR_{ij} refers principal component of the average value of five climate-related indicators for i and j. $Sim_{ij,t-1}^{Econ}$ refers to the first principal component of absolute differences in real GDP growth, real interest rate, inflation rate and term spreads, and converted such that a larger $Sim_{ij,t-1}^{Econ}$ represents smaller differences in all four indicators. refers to the geographical distance (in logarithm) between the capital cities of countries i and j. $Sizediff_{ij}$ refers to the absolute differences in stock market size (as % of GDP). $import_{ij}$ stands for the average of the ratio of country i import from country j to total import of country i and the ratio of country j import from country i to total import of country j. $export_{ij}$ stands for the average of the ratio of country i export to country j to total export of country i and the ratio of country j export to country i to total export of country j. $import_{ij}$ is further regressed on $export_{ij}$ before applying the regression residuals in estimation. $fxchange_sd_{ij,t-1}$refers to annualized standard deviation of daily percentage change in bilateral exchange rate. vix denotes the VIX index (in logarithm and multiplied by 100). dum^{PA} denotes a time dummy variable that covers annual observations after the announcement of Paris Agreement in 2015. Except $Comove_{ij}$, CR_i, and vix, all continuous variables are winsorised at 2.5% and 97.5% before estimation. ***, ** and * represent 1%, 5% and 10% significance level respectively. Robust standard errors are presented at the parentheses. The annual sample covers 2004 to 2020 and excludes thin-trading stock market pairs (annual turnover rank below one-third of all sample markets for both markets).

Panel a: Estimation results of Equation 3

	Dependent variable: $Comove_{ij,t}$	
	(1)	(2)
$CR_{ij,t-1}$	**2.96*** **	**2.65*** **
	(0.82)	(0.87)
$CR_{ij,t-1} * dum_t^{PA}$		**2.21*** **
		(0.36)
$Sim_{ij,t-1}^{Econ}$	**1.05*** **	**1.02*** **
	(0.16)	(0.18)
$Sizediff_{ij,t-1}$	**-0.02*** **	**-0.02** **
	(0.01)	(0.01)
$import_{ij,t-1}$	**0.49** **	**0.56** **
	(0.25)	(0.25)
$export_{ij,t-1}$	0.25	0.32
	(0.22)	(0.23)
$fxchange\_sd_{ij,t-1}$	0.93	2.07
	(4.89)	(4.95)
vix_t	**0.33*** **	**0.33*** **
	(0.01)	(0.01)
Observations	4087	4087
Number of country pairs	324	324
GFC control	Yes	Yes
COVID control	Yes	Yes
R^2	0.44	0.44
Adjusted R^2	0.39	0.39

Panel b: Estimation results of Equation 4

	Dependent variable: $Comove_{ij,t}$			
	(1)	(2)	(3)	(4)
$Factor_{ij,t-1}$	$Sim^{Econ}_{ij,t-1}$	$Dist_{ij,t-1}$	$Sizediff_{ij,t-1}$	$import_{ij,t-1}$
$CR_{ij,t-1}$	**2.87*****	-3.43	**2.68*****	**2.78*****
	(0.81)	(7.33)	(0.87)	(0.82)
$CR_{ij,t-1} * Factor_{ij,t-1}$	**0.39****	0.73	0.01	**0.41****
	(0.16)	(0.84)	(0.01)	(0.20)
$Sim^{Econ}_{ij,t-1}$	**0.85*****	**1.05*****	**1.05*****	**1.04*****
	(0.19)	(0.16)	(0.16)	(0.16)
$Sizediff_{ij,t-1}$	**-0.02****	**-0.02****	-0.01	**-0.02****
	(0.01)	(0.01)	(0.01)	(0.01)
$import_{ij,t-1}$	**0.49****	**0.49****	**0.49****	0.38
	(0.25)	(0.24)	(0.25)	(0.24)
$export_{ij,t-1}$	0.25	0.24	0.25	0.20
	(0.22)	(0.22)	(0.22)	(0.22)
$fxchange\_sd_{ij,t-1}$	-0.12	0.66	0.93	1.10
	(4.91)	(4.95)	(4.87)	(4.87)
vix_t	**0.33*****	**0.33*****	**0.33*****	**0.33*****
	(0.01)	(0.01)	(0.01)	(0.01)
Observations	4087	4087	4087	4087
Number of country pairs	324	324	324	324
GFC control	Yes	Yes	Yes	Yes
COVID control	Yes	Yes	Yes	Yes
R^2	0.41	0.41	0.41	0.41
Adjusted R^2	0.36	0.36	0.36	0.36

Table 6: Estimated effect of countries' climate change performance on climate transition risk spillover

This table reports the estimated effect of countries' climate change performance on climate transition risk spillover. Column 1 reports the baseline estimates of Equation 5, Column 2 to 3 report sub-sample analysis of Equation 5, while Column 4 report the results of revised Equation 3 which separates the estimated β_{CR} according to the number of countries with good climate change performance (footnote 21). $Comove_{ij,t}$ denotes the unconditional correlation between daily stock market returns of two country i and j in year t (Equation 2). CR_{ij} refers principal component of the average value of five climate-related indicators for i and j. $Performance_{ij,t-1}$ refers to the average CCPI rating of countries i and j in year t-1. $D^{both}_{ij,t-1}$ is a dummy variable equals to one when the CCPI rating equals to or above "medium" rating for both country i and j in year *t-1*, and zero vice versa. D^{sing}_{ij} is a dummy variable equals to one when the CCPI rating equals to or above "medium" in either country i and j (but not both) in year *t-1,* and zero vice versa. $Sim^{Econ}_{ij,t-1}$ refers to the first principal component of absolute differences in real GDP growth, real interest rate, inflation rate and term spreads, and converted such that a larger $Sim^{Econ}_{ij,t-1}$ represents smaller differences in all four indicators. $Sizediff_{ij}$ refers to the absolute differences in stock market size (as % of GDP). $import_{ij}$ stands for the average of the ratio of country i import from country j to total import of country i and the ratio of country j import from country i to total import of country j. $export_{ij}$ stands for the average of the ratio of country i export to country j to total export of country i and the ratio of country j export to country i to total export of country j. $import_{ij}$ is further regressed on $export_{ij}$ before applying the regression residuals in estimation. $fxchange\_sd_{ij,t-1}$ refers to annualized standard deviation of daily percentage change of bilateral exchange rate. vix denotes the VIX index (in logarithm and multiplied by 100). Except $Comove_{ij,t}$, CR_{ij} and vix all continuous variables are winsorised at 2.5% and 97.5% before estimation. ***, ** and * represent 1%, 5% and 10% significance level respectively. Robust standard errors are presented at the parentheses. The annual sample covers 2011 to 2020 and excludes thin-trading stock market pairs (annual turnover rank below one-third of all sample markets for both markets).

	(1)	(2)	(3)	(4)
$CR_{ij,t-1}$	**6.43*****	**8.67*****	**4.61***	**4.87*****
	(1.80)	(2.42)	(2.59)	(1.41)
$CR_{ij,t-1} * Performance_{ij,t-1}$	**-1.44*****	**-2.55*****	-1.12	
	(0.54)	(0.74)	(0.71)	
$CR_{ij,t-1} * D^{Both}_{ij,t-1}$				**-3.65*****
				(0.96)
$CR_{ij,t-1} * D^{Sing}_{ij,t-1}$				**-1.40****
				(0.59)
$Performance_{ij,t-1}$	-0.57	-2.15	0.57	
	(0.74)	(0.94)	(1.17)	
$D^{Both}_{ij,t-1}$				-0.89
				(1.31)
$D^{Sing}_{ij,t-1}$				0.39

				(0.76)
$Sim^{Econ}_{ij,t-1}$	**0.61****	-1.59	**0.85*****	**0.59*****
	(0.21)	(1.81)	(0.24)	(0.21)
$Sizediff_{ij,t-1}$	**-0.03***	**-0.04*****	-0.01	**-0.02***
	(0.01)	(0.01)	(0.02)	(0.01)
$import_{ij,t-1}$	**0.76***	1.04	0.75	**0.72***
	(0.43)	(0.90)	(0.51)	(0.41)
$export_{ij,t-1}$	**0.70***	0.40	0.61	**0.66***
	(0.39)	(0.60)	(0.53)	(0.40)
$fxchange\_sd_{ij,t-1}$	**0.00****	**0.00****	0.00	0.04
	(0.00)	(0.00)	(0.00)	(0.04)
vix_t	**0.35*****	**0.36*****	**0.34*****	**0.34*****
	(0.01)	(0.02)	(1.70)	(0.01)
Observations	1824	870	954	1824
Number of country pairs	187	167	165	187
COVID control	Yes	Yes	Yes	Yes
R^2	0.51	0.53	0.53	0.51
Adjusted R^2	0.45	0.42	0.42	0.45
Sample	All	$Sim^{Econ}_{ij,t-1}>$ sample median	$Sim^{Econ}_{ij,t-1}<=$ sample median	All

Annex A: Definition of control variables

Control variables in Equation 1

Variables	Description	Source(s)
$Stock\ market\ size\ (size_i)$	stock market capitalization of country i's MSCI stock market index as percentage of country i's GDP	Bloomberg
$Book\ to\ market\ value\ ratio\ (bm_i)$	Book value divided by market value of country i's MSCI stock market index.	Bloomberg
$Dividend\ yield\ (divy_i)$	Dividend yield of country i's MSCI stock market index.	Bloomberg
$Inflation\ rate\ (infl_i)$	Annual growth rate of consumer price index in country i.	World Bank World Development Indicators
$Real\ GDPgrowth\ (gdpg_i)$	Annual growth rate of per capital real GDP growth in country i.	World Bank World Development Indicators
$Term\ spread\ (ts_i)$	The difference between long term government bond rate and short term government bond rate of country i.	IMF International Financial Statistics
$Real\ interest\ rate\ (rint_i)$	Nominal short-term interest rate minus inflation rate of country i.	World Bank World Development Indicators, IMF International Financial Statistics
$Exchange\ rate\ (fxchange_i^{USD})$	Annualized daily percentage change of country i's exchange rate against the USD.	Bloomberg
$VIX\ index\ (vix)$	Logarithms transformation of CBOE volatility (VIX) index, multiplied by 100	Bloomberg

<u>Control variables in Equation 3 to 5</u>

Variables	Description	Source(s)
Similarity in economic condition ($Econsim_{ij,t-1}$)	The first principal component of the absolute differences in real GDP growth, real interest rate, inflation rate and term spreads between country i and j. A more positive value denotes smaller absolute differences in the aforementioned variables (i.e. more similar in economic condition).	World Bank World Development Indicators, IMF International Financial Statistics
Differences in stock market sizes ($Sizediff_{ij,t-1}$)	Absolute differences in stock market size (as % of GDP) of country i and j.	Bloomberg
Import dependence ($import_{ij,t-1}$)	The average of i) country i's imports from j (as a percentage of i's total imports) and ii) country j's imports from i (as a percentage of j's total imports)	IMF Direction of Trade Statistics
Export dependence ($export_{ij,t-1}$)	The average of i) country i's exports to j (as a percentage of i's total exports) and ii) country j's exports to i (as a percentage of j's total exports)	IMF Direction of Trade Statistics
Exchange rate volatility $fxchange\_sd_{ij,t-1}$	The annualized standard deviation of daily percentage change of the bilateral exchange rate for country i and j.	Bloomberg
VIX index (vix)	Logarithms transformation of CBOE volatility (VIX) index, multiplied by 100	Bloomberg

Annex B: Summary of amplification factors

Amplification factor	How it may amplify the spillover of climate transition risks?
Similarity in economic condition	Countries are more likely to adopt similar climate policies, sooner or later, if they share similar economic conditions.
Geographical distance	Two neighbourhood countries are expected to align more with climate policies as they are more likely to be affected by each other's climate incidents.
Stock market size differences	The expectation channel is likely to exert a larger impact on the stock markets with similar sizes.
Import dependence	A country could be affected by the climate policies of others if it imported more from them, such that they have to bear the costs (e.g., carbon tax) through imports (and therefore a rise in climate transition risk).

Annex C: List of countries used in the sample

Advanced countries	**Emerging market countries**
Americas:	*Americas:*
Canada	Brazil
United States	Chile
	Mexico
Europe & Middle East:	Peru
Austria	
Belgium	*Europe, Middle East & Africa:*
Denmark	Czech Republic
Finland	Egypt
France	Greece
Germany	Poland
Ireland	Russia
Israel	South Africa
Italy	Turkey
Netherlands	Kazakhstan
Portugal	Romania
Spain	Slovenia
Sweden	
Switzerland	*Asia:*
United Kingdom	China
	India
Pacific:	Korea
Australia	Philippines
Japan	Thailand
New Zealand	Bangladesh
Singapore	Sri Lanka
	Vietnam