

The propagation effect of climate risks on global stock markets: Evidence from the time and space domains

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ABSTRACT

This study delves into the propagation effect of climate risks on global stock markets, emphasizing the dynamics of contagion. We first trace the contagion pathway of climate risks across global stock markets, revealing an initial diffusion to Asian markets, followed by European markets, and ultimately reaching American markets. The HSI (Hong Kong, China), DAX (Germany), and SZ (China) markets emerge as pivotal nodes for the indirect transmission of overall climate risk. Additionally, we scrutinize the propagation dynamics of climate risks across varying timescales, noting a heightened magnitude and swifter pace at short-timescale compared to the long-timescale. Lastly, we conduct a comparative analysis of the propagation impact of distinct types of climate risks, identifying drought and precipitation risks as exerting a more pronounced influence on stock markets, both in terms of propagation speed and magnitude, relative to temperature risks.

1. Introduction

Climate change stands as one of the paramount challenges demanding immediate attention (Nordhaus, 2019; Masson-Delmotte et al., 2021; Pankratz et al., 2023; Sautner et al., 2023). A burgeoning body of academic literature explores its impacts, encompassing investigations into the effectiveness of climate policies (Bartram et al., 2022; Ouazad and Kahn, 2022), its ramifications on stock markets (Smith, 2018; Hong et al., 2019; Alok et al., 2020), bond markets (Painter, 2020; Huynh and Xia, 2021; Cevik and Jalles, 2022), real estate markets (Bakkensen and Barrage, 2022; Giglio et al., 2021; Hu and Lee, 2020), and derivatives markets (Schlenker and Taylor, 2021; Ilhan et al., 2021). While this body of literature has provided valuable insights into the impact of climate change, there remain three unanswered questions.

Firstly, the mechanism of market interplay concerning climate change remains ambiguous. Existing studies have predominantly focused on either individual markets or employed panel regressions to analyze multiple markets. However, given the interdependencies between markets—wherein climate risk may disseminate from one market to another, creating a chain reaction of influence—it is imperative to investigate the transmission dynamics of climate change across markets. Secondly, it has been observed that shocks to economic activity manifest with varying frequencies and intensities (Dew-Becker and Giglio, 2016;

Baruník and Křehlík, 2018; Bandi and Tamoni, 2023). Given that the stock market serves as a barometer of economic health, it responds differentially to shocks of disparate frequencies. Consequently, market participants are compelled to navigate decisions across short-, medium-, and long-term timescales (Tiwari et al., 2018), prompting inquiry into how markets react to climate risks across these temporal scales. Thirdly, Chen et al. (2023) underscore the heterogeneity of climate risks, noting earthquakes as exerting the most potent influence while storms exhibit the weakest impact. Furthermore, financial institutions display varying responses to different types of climate risks. Hence, it begs the question of whether disparities exist in global stock markets' responses to distinct types of climate risks. Therefore, this study endeavors to address these three inquiries by scrutinizing the propagation effect of climate risks on 16 global stock market indexes spanning five continents, thereby bridging extant research lacunae.

Specifically, we employ a Ripple-Spreading Network Model (RSNM) from a ripple network perspective to explore the interaction effect between markets. This method encompasses five key parameters: initial risk energy, amplification capacity, resilience capacity, market distance, and risk propagation speed. The RSNM is well-suited for our study objectives for several reasons. Firstly, it delineates the dynamic process of gradual climate risk propagation within global stock markets and traces risk transmission within contaminated markets, enabling the study of

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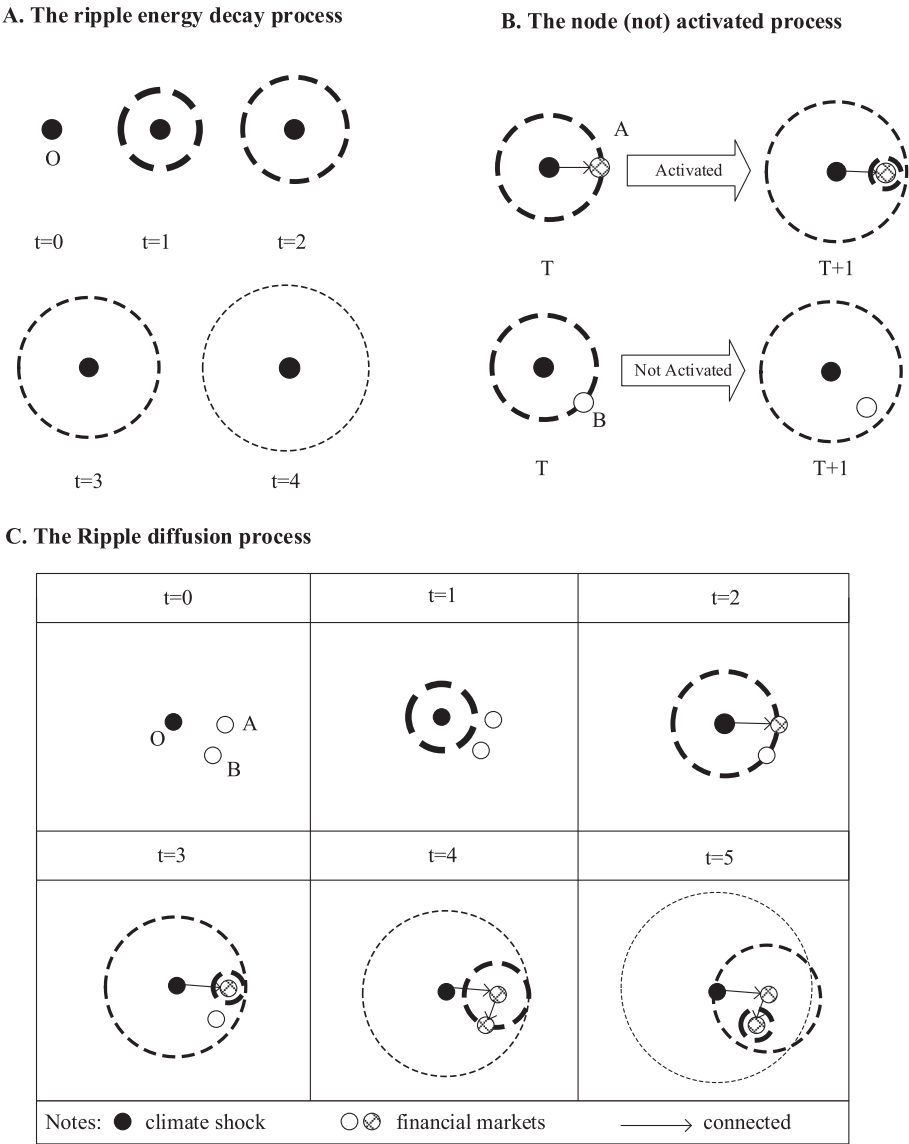


Fig. 1. A simple example of the risk ripple diffusion process.
Notes: This illustration provides a basic example depicting the propagation process of the Ripple-Spreading Network Model (RSNM). For simplicity, we consider two financial markets labeled A and B. Market O serves as the wave source.

Table 1
Descriptive statistics for climate risk series.

	N	Mean	SD	Min	Max
Climate risk	11,748	0.0000	64.6368	−283.3394	285.0338
Temperature risk	11,748	0.0110	6.9681	−29.5660	31.0635
Drought risk	11,748	0.0000	0.0001	−0.0019	0.0018
Precipitation risk	11,748	0.0114	11.4299	−160.3584	152.2800

Notes: This table presents descriptive statistics for four climate risks. The first climate risk corresponds to the first principle of the eight dimensions of climate data. Each column displays the number of observations, mean, standard deviation, minimum value, maximum value, skewness, and kurtosis for each risk.

market interaction effects. Secondly, it facilitates the analysis of dynamic contagion of climate risk across different timescales by calculating these parameters for each node market in the short, medium, and long term. Thirdly, it enables exploration of differences in the impact of different types of climate risks by comparing contagion scale and speed for each climate risk.

In terms of climate risk variables, we incorporate eight dimensions of

climatic data, specifically humidity, wind speed, net radiation, latent heat flux, soil moisture, standardized precipitation index representing drought, precipitation, and temperature. To capture the comprehensive nature of climate risk, we derive the first principal component as a proxy variable. Additionally, we conduct separate analyses to assess the impacts of temperature, drought, and precipitation. There are two primary rationales guiding our choice. Firstly, previous research has predominantly focused on singular climate risks (Hong et al., 2019; Bakkensen and Barrage, 2022; Lee et al., 2022) or limited their examination to a few commonly explored dimensions (Bonato et al., 2023). In contrast, our study adopts a more inclusive approach by considering eight dimensions, thus providing a more comprehensive assessment. Secondly, recognizing the heterogeneity inherent in climate risks (Chen et al., 2023), our approach aims to compare the effects of different climatic factors. As such, we investigate three widely studied climate risks—temperature (Lee et al., 2022), drought (Hong et al., 2019), and precipitation (Bakkensen and Barrage, 2022). Our analysis not only compares these three types of climate risks among themselves but also contrasts them with the overall climate risk.

We find that climate risks have a great impact on the 16 global stock

Table 2

Descriptive statistics for financial markets' return series.

Continent	Country	Financial markets	Ticker	N	Mean	SD	Min	Max	
North America	America	S&P500	SPX.GI	SPX	8074	0.03	1.14	−12.77	10.96
	America	Dow Jones Industrial Index	DJI.GI	DJI	8074	0.03	1.11	−13.84	10.76
	America	NASDAQ index	IXIC.GI	IXI	8074	0.04	1.46	−13.15	13.26
South America	Brazil	Brazilian IBOVESPA index	IBOVESPA.GI	IBO	8074	0.21	2.74	−39.30	34.21
	China	SHSZ Composite Index	000001.SH	SH	8074	0.05	2.16	−17.91	71.92
Asia	China	SZSE Composite Index	399,001.SZ	SZ	8074	0.03	2.05	−22.04	23.46
	Taiwan, China	Taiwan-weighted index	TWII.TW	TW	8074	0.01	1.59	−12.78	12.84
	Hong Kong, China	Hang Seng Index	HSI.HI	HSI	8074	0.03	1.53	−14.74	17.25
	Korea	Korea Composite Index	KS11.GI	KS	8074	0.01	1.63	−13.27	11.28
	Japan	Nikkei 225	N225.GI	N225	8074	−0.01	1.47	−12.11	13.24
	India	Indian SENSEX30	SENSEX.GI	SEN	8074	0.05	1.60	−14.10	18.90
	Germany	German DAX	GDAXI.GI	DAX	8074	0.03	1.42	−13.06	10.80
Europe	France	French CAC 40	FCHI.GI	CAC	8074	0.02	1.38	−13.10	10.60
	United Kingdom	UK FTSE 100	FTSE.GI	FTS	8074	0.01	1.11	−11.51	9.38
	Russia	Russian RTS	RTS.GI	RTS	8074	0.03	2.31	−50.15	23.20
Oceania	Australia	S&P Australia200	AS51.GI	AS	8074	0.02	0.95	−10.26	6.77

Notes: This table showcases descriptive statistics for stock futures markets' return series. Each column exhibits the financial markets' continent, country, name, ticker, the number of observations, mean, standard deviation, minimum value, maximum value, skewness, and kurtosis for each market. Tickers are used for simplicity.

Table 3

Parameters for climate risk and financial markets.

	α_i	β_i	$\beta_{i,1}$	$\beta_{i,2}$	$\beta_{i,3}$	s_i		α_i	β_i	$\beta_{i,1}$	$\beta_{i,2}$	$\beta_{i,3}$	s_i
climate risk	0	74,669.68	1301.82	5930.53	106,749.59	0.02	drought risk	0	35,290.13	742.21	3062.40	50,335.86	0.02
temperature risk	0	80,190.23	1354.98	6359.58	114,647.49	0.02	precipitation risk	0	15,096.33	486.94	1477.73	21,454.64	0.02
SPX	4.53	80.70	1.41	6.41	115.37	0.02	KS	6.56	169.06	2.95	13.43	241.69	0.03
DJI	4.41	86.10	1.50	6.84	123.10	0.02	N225	6.26	151.61	2.64	12.04	216.75	0.03
IXI	5.80	101.84	1.78	8.09	145.60	0.02	SEN	6.55	282.18	4.93	22.44	403.39	0.04
IBO	10.31	304.47	5.31	24.19	435.27	0.02	DAX	5.84	78.44	1.37	6.23	112.14	0.02
SH	7.61	206.72	3.61	16.43	295.53	0.03	CAC	5.76	75.94	1.32	6.03	108.56	0.02
SZ	8.12	189.22	3.30	15.03	270.51	0.03	FTS	4.55	79.06	1.38	6.28	113.03	0.02
TW	6.41	243.62	4.25	19.36	348.28	0.03	RTS	8.08	196.46	3.43	15.61	280.86	0.02
HSI	6.29	103.83	1.81	8.25	148.43	0.02	AS	3.79	126.52	2.21	10.05	180.87	0.03

Notes: This table provides parameters for four types of climate risks and 16 stock markets. Each column presents the ability of the market to amplify the strength of innovations after being activated (α_i), the resilience capacity of the market to resist innovations (β_i), the resilience capacity of the market to resist innovations in short, medium, and long timescales ($\beta_{i,1}$, $\beta_{i,2}$, and $\beta_{i,3}$), and the speed of the market to spread innovations outward (s_i) for each risk and market.

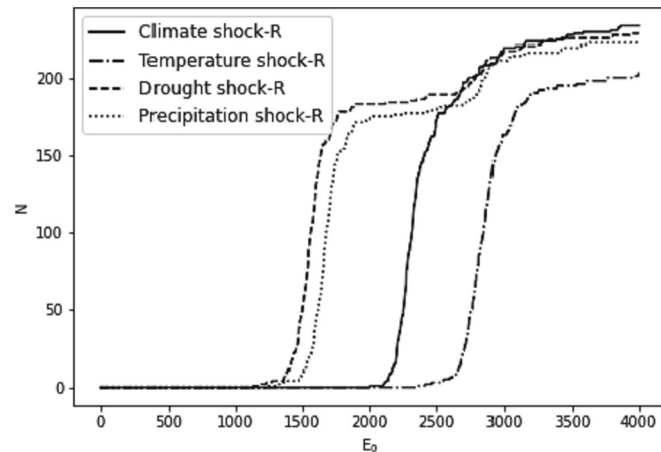


Fig. 2. Relationship between E_0 and N under four climate risks.

Notes: E_0 denotes the initial wave source energy value, while N represents the total edges of the stable network. The labels “Climate shock-R,” “Temperature shock-R,” “Drought shock-R,” and “Precipitation shock-R” indicate the overall climate risk, temperature risk, drought risk, and precipitation risk's impact on returns across 16 global stock markets, respectively.

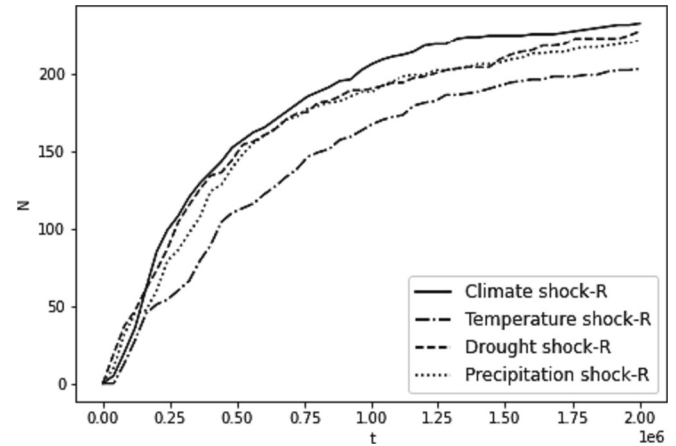


Fig. 3. The dynamic variation of N with t under different climate risks.

Notes: This figure illustrates the variation of N (total edges of the stable network) with t (time) under various climate risks. The subplots represent different climate risks' impacts on returns across 16 global stock markets. The results are obtained with a wave source energy set at 20,000 for each of the four subplots.

market indexes, both for the overall climate risk and for a particular climate risk. Regarding timescales, we observe that short-term climate risks propagate most rapidly and generate the highest number of stable

network edges. Furthermore, short-term transmission pathways outnumber those in the long term. In terms of climate risk types, overall climate risk affects the highest number of stock markets, followed by

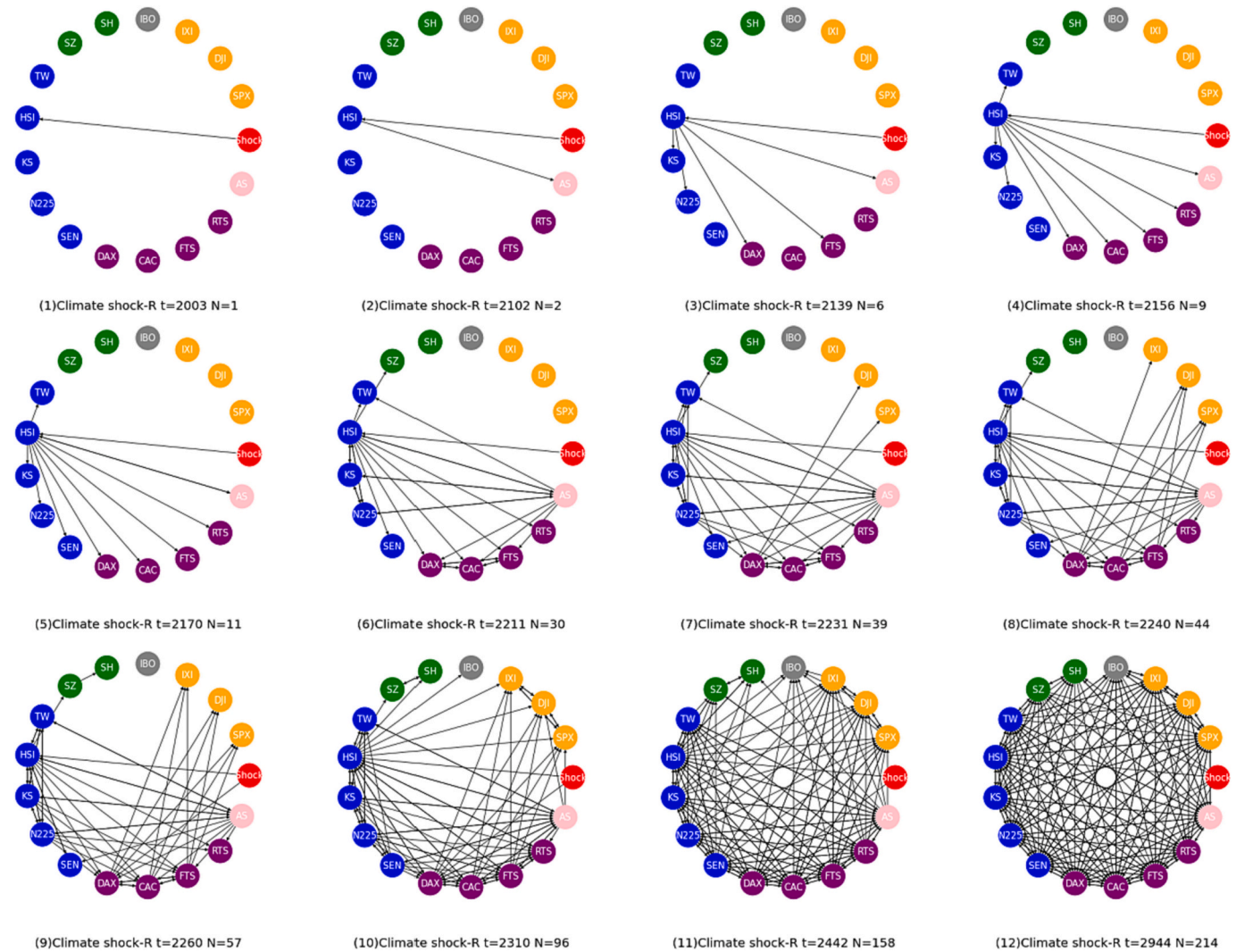


Fig. 4. Dynamic ripple diffusion process based on overall climate risk-R network.

Notes: Each subplot in this figure represents an instantaneous risk ripple network at a specific moment, with the “shock” representing the overall climate risk and other nodes representing stock markets across different regions. The red nodes represent the overall climate risk, orange nodes represent stock markets in North America, gray nodes represent markets in South America, green nodes represent stock markets in mainland China, blue nodes represent other stock markets in Asia, purple nodes represent stock markets in Europe, and pink nodes represent stock markets in Oceania. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

drought and precipitation risks, with temperature risk exhibiting the lowest impact. Additionally, drought risk is the first to affect stock markets, followed by precipitation risk, overall climate risk, and finally temperature risk. Moreover, the propagation of overall climate risks primarily occurs through the HSI (Hong Kong, China), DAX (Germany), and SZ (China) markets, while temperature risks mainly spread through the SH (China), HSI, DAX, and RTS (Russia) markets, and drought and precipitation risks primarily propagate through the SZ, HSI, and DAX markets.

This research makes four contributions to the existing literature. Firstly, this research marks the pioneering attempt to investigate the propagation of climate risk in global stock markets and to explore the contagion process from both temporal and spatial perspectives. In the time dimension, we know how climate risks are transmitted over time throughout the global stock markets, and we can also see how the number of network edges changes over time. In the spatial dimension, we can identify the transmission process of risks for each node, including when they were first infected and when they were last infected. By scrutinizing the transmission dynamics of climate risks over time and across different markets, we offer a comprehensive understanding of

how climate risks propagate within the global financial system.

Secondly, we contribute to the literature by examining the propagation effect of climate risks on global stock markets across various timescales. While prior studies on frequency analysis have primarily focused on spillover network analysis within global crude oil markets (Ouyang et al., 2021), interactions between the crude oil market and stock markets (Zhang and Hamori, 2021), relationships between the oil market and airline stocks (Asadi et al., 2023), and connections between the European Emissions Trading System (ETS) and sustainability markets (Suleman et al., 2023), the field of climate risk remains largely unexplored, to the best of our knowledge. We identify distinct variations in the propagation of climate risks across different timescales, encompassing differences in propagation speed and scale. Hence, our investigation into major global stock markets offers novel insights into the frequency analysis of climate risks.

Thirdly, despite the expanding literature providing valuable insights into various types of climate risk, the dynamic spillover effects of different types of climate risks remain elusive. Previous studies have predominantly focused on investigating specific climate risks, such as temperature (Lee et al., 2022), drought (Hong et al., 2019), and

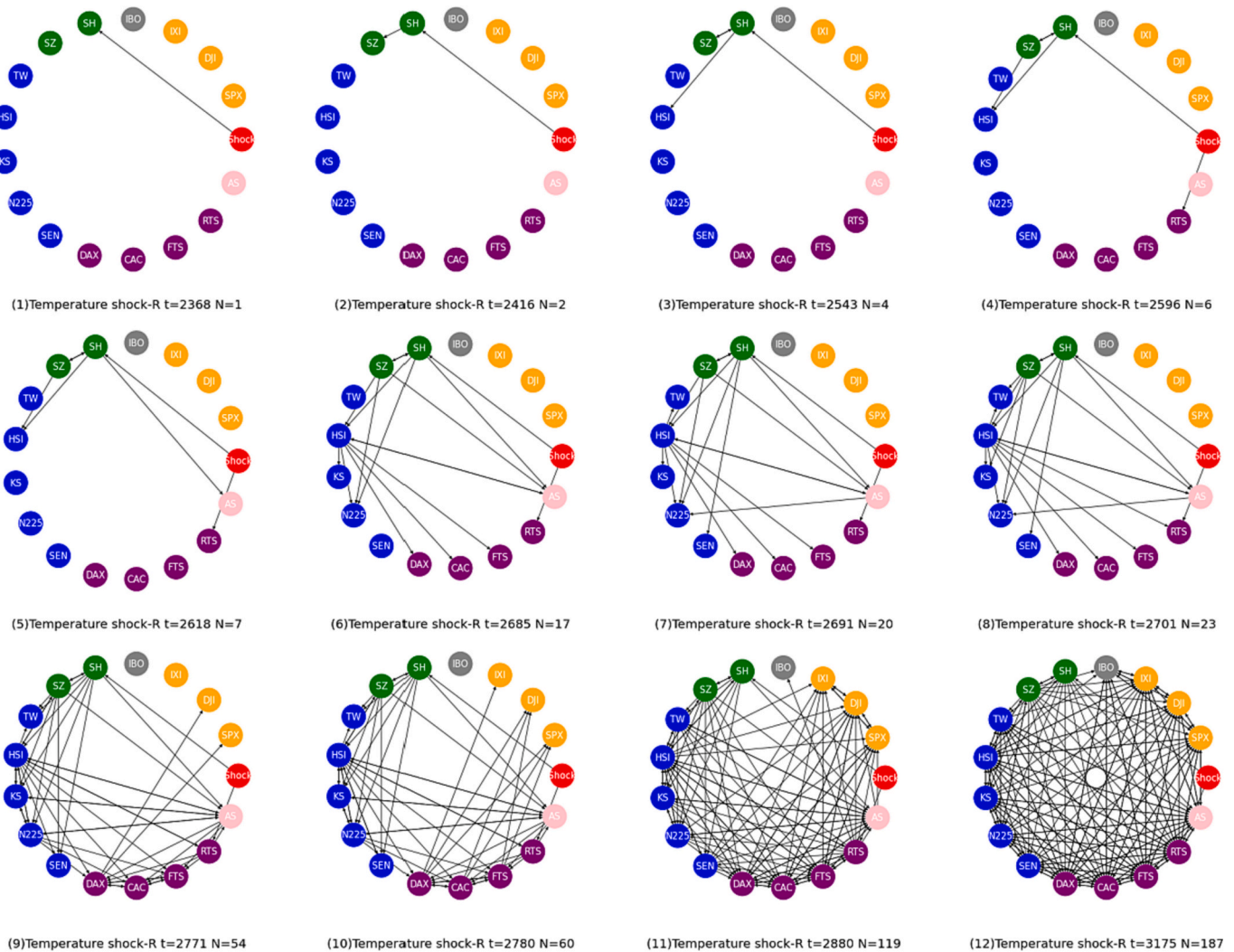


Fig. 5. Dynamic ripple diffusion process based on temperature risk-R network.

Notes: Similar to Fig. 4, here the “shock” represents the temperature risk, while other nodes represent stock markets across different regions.

precipitation (Bakkensen and Barrage, 2022), or have explored multi-dimensional climate risks for forecasting purposes, as demonstrated by Bonato et al. (2023), who utilized five dimensions of climate risk’s realized volatility to forecast exchange rate returns. Additionally, there are studies employing climate policy uncertainty as a proxy for overall climate risk to examine its impact on key energy markets (Rao et al., 2023). However, few studies have undertaken comparisons of the effects of different types of climate risks on stock markets. This study serves as a supplement in this regard, as we not only compare the impacts of specific types of climate risks among themselves but also juxtapose them with the overarching climate risk.

Lastly, our findings offer actionable insights for market participants to mitigate climate risk across various financial markets and investment horizons, tailored to each type of climate risk. Previous literature on climate risk management often presents modeling-based approaches to identify parameters for risk management. For instance, Berger et al. (2017) propose a risk management framework to address climate change disasters, emphasizing the impact of model uncertainty and disagreement on determining optimal abatement strategies. In contrast to these approaches, our research provides practical solutions for climate risk management. By delineating the specific transmission pathways of risks to financial markets and discerning the timing of risk arrival in each market, we can offer concrete recommendations. For instance, during climate risk events, financial markets can prioritize

monitoring those stock markets identified as early transmitters of risk. Furthermore, our identification of distinct climate risk propagation processes across different timescales serves as a vital reference for market participants with diverse investment horizons.

The remainder of the paper is organized as follows: Section 2 introduces the methodology, Section 3 presents the data, Section 4 analyzes the empirical results, and Section 5 concludes.

2. Method

This paper employs the Ripple-Spreading Network Model (RSNM) proposed by Hu et al. (2011) to explore the dynamic transmission of climate risks within financial markets. The RSNM model facilitates the visualization of the gradual propagation of risk throughout the system. Moreover, it enables the analysis of variations in risk contagion among individual markets at any specific juncture. Consequently, we can track the transmission of risk, distinguishing between direct transmission and transmission via intermediary financial markets.

The RSNM offers several advantages. Firstly, it effectively captures the gradual dissemination of information, providing a clear depiction of its spread over time. Secondly, by leveraging the RSNM, we can assess not only the scale and speed of information spillover but also map out the pathways through which information propagates. This approach enables us to monitor and comprehend the progression of information

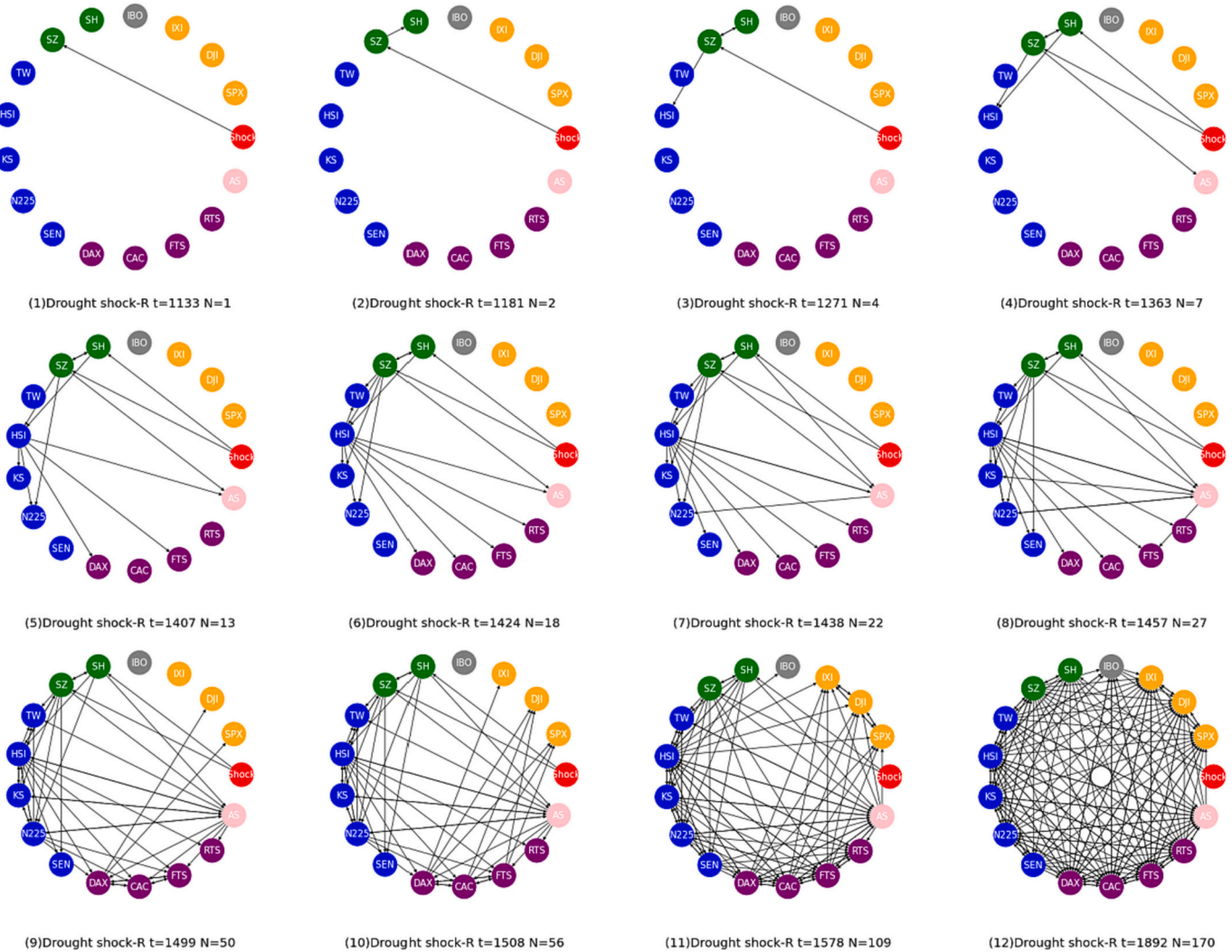


Fig. 6. Dynamic ripple diffusion process based on drought risk-R network.

Notes: In this figure, the “shock” represents the drought risk, while other nodes depict stock markets across different regions.

dissemination at any given moment. Thirdly, the RSNM is versatile in analyzing the interplay between various timescales and evaluating the influence of different risk factors. It serves as a valuable tool for examining the combined effects of different temporal scales and assessing the impact of diverse risks.

To construct the RSNM model, five key parameters must be defined: the initial energy value of the risk or wave source (E_0), the energy of the new wave source produced by the market i after being activated (E_i); the speed at which the initial ripple generated by the risk spread outward (s_0), the market i 's outward propagation speed (s_i); the market distance between the risk source and the individual stock market i ($D(O, i)$), and the distance between market i and market j ($D(i, j)$); the market i 's ability to amplify the risk upon being shocked (α_i); and the threshold (β_i) at which market i can be infected by the risk if β_i is smaller than the reached energy. In this model, the energy E_0 and E_i are assumed to decay continuously as the ripples propagate, following the equation $f_{Decay}(E_i, r_i, t) = \frac{\eta E_i}{2\pi r_i t}$, where η represents the energy decay coefficient and r_i denotes the ripple radius at time t . Notably, the concept of time is relative and used solely to investigate the gradual diffusion process of innovations, without corresponding to real-world time intervals or specific dates. By employing time in this manner, we can effectively study and analyze the temporal dynamics of information spillover in a controlled and systematic manner.

We provide a simple example of the risk diffusion process in Fig. 1. Panel A depicts the risk source's energy decay process, with the thickness of the circle line representing the strength of the risk and the radius of the circle equaling the speed multiplied by time. As time progresses, the ripple's circle radius ($r_0(t)$) enlarges, while the energy ($e_0(t)$) decays. Panel B illustrates the node's activated process. When the ripple circle's radius ($r_0(T)$) equals the distance between ripple source and the market A ($r_0(T) = D(O, A)$), the risk reaches the market A at the time T . If the reached energy ($e_0(T)$) exceeds market A's resilience capacity (β_A), the market A is activated and induce a new ripple at time $T + 1$. The energy of the induced ripple ($E_A(T + 1)$) equal the reached energy multiply the amplification risk capacity of market A ($e_0(T) * \alpha_A$). If the reached energy ($e_0(T)$) is smaller than market B's resilience capacity (β_B), market B remains inactive and cannot induce a new ripple at time $T + 1$.

Panel C of Fig. 1 depicts a simple diffusion process of a system with a risk source O and two stock markets A and B. At $t = 0$, the risk source O initiates risk propagation.

At $t = 1$, the ripple circle of risk source O spreads outside with the speed of s_0 . Since the distances between the risk source and the markets are greater than the respective radii of the ripple circles ($r_0(1) < D(O, A)$ and $r_0(1) < D(O, B)$), the risk has not reached any node market.

At $t = 2$, the ripple circle of risk source O reaches market A and B simultaneously ($r_0(2) = D(O, A)$, and $r_0(2) = D(O, B)$). The market A is

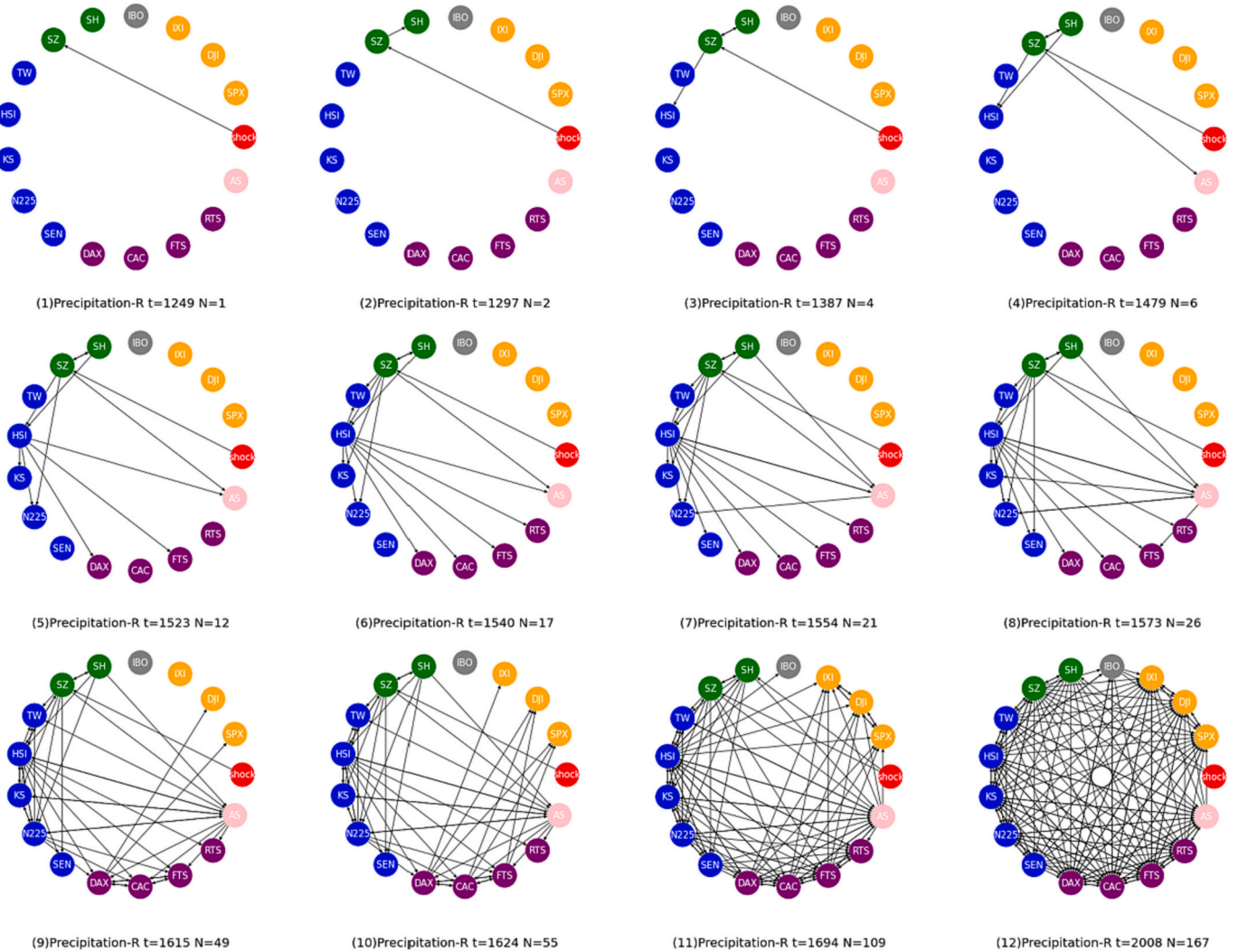


Fig. 7. Dynamic ripple diffusion process based on precipitation risk-R network.

Notes: Here, the “shock” symbolizes the precipitation risk, while other nodes portray stock markets across different regions.

activated ($e_O(2) \geq \beta_A$), while market B remains inactive ($e_O(2) < \beta_B$). Consequently, a connected edge is established from risk source O to market A ($M(OA) = 1$, while M is an adjacent matrix).

Subsequently, at $t = 3$, the risk source O continues to propagate, with the activated market A propagating risk at a speed of s_A , inducing a new ripple with an energy of $e_A(3) = \alpha_A e_O(2)$.

At $t = 4$, the ripple induced by market A reaches the market B ($r_A(4) = D(A, B)$), activating it and establishing a connected edge from market A to market B ($M(AB) = 1$).

At $t = 5$, the risk source O, activated market A, and activated market B continue to propagate, with the speed of s_O , s_A and s_B , respectively.

In this example, there are two edges. Market A is directly propagated by market O at $t = 2$ while market B is indirectly impacted by market A at $t = 4$. Through the transmission processes of this wave source (O), we observe that: 1) in the temporal domain, we can monitor the change in all connected edges over time; 2) in the spatial domain, we can visualize the spillover network at any specific point in time; and 3) by combining these two domains, we can track each pathway reaching a particular market and determine the corresponding time of its arrival.

3. Data

3.1. Measurement of climate risk

In this study, we obtain daily climate data from the Climate Engine platform,¹ an online platform for analyzing Earth observation and remote sensing data supported by NASA and USGS. The data encompass eight dimensions on a global scale, including humidity, wind speed, net radiation, latent heat flux, soil moisture, standardized precipitation index (drought), precipitation, and temperature, spanning from 2 January 1990 to 28 February 2022. To remove the seasonal trends in climate data, we apply a differencing technique to all eight indicators. Following the approach outlined in Lee et al. (2022), we calculate the anomalous climate data using Eq. (1).

$$\tau_t = T_t - \left(\frac{1}{t} \right) \sum_{j=1}^t T_{t-j} \quad (1)$$

Where τ_t represents the anomalous climate data, T_t refers to the corresponding climate data at a specific time, and $\left(\frac{1}{t} \right) \sum_{j=1}^t T_{t-j}$ denotes the mean climate data over the sample period. After data processing, we derive daily anomalous climate data in eight dimensions. Given the high

¹ <https://app.climateengine.org/climateEngine>.

Table 4

The path and timing of climate risk transmission to representative stock markets.

	SPX	DAX	SH	RTS
Total number of paths	15	14	11	13
Total number of nodes	15	15	10	13
Key node 1 (times)	HSI(15)	HSI(14)	HSI(10)	HSI(13)
Key node 2 (times)	DAX(3)	DAX(3)		DAX(3)
Key node 3 (times)	SZ(2)	SZ(2)		
The first contagion	risk→HSI → DAX → SPX(t = 2231)	risk→HSI → DAX(t = 2139)	risk→HSI → SZ → SH(t = 2260)	risk→HSI → RTS(t = 2156)
Infected by the overall climate risk			risk→SH(t = 2621)	
Infected by Americas		risk→HSI → DAX → SPX → DAX(t = 2324)		risk→HSI → DAX → SPX → RTS(t = 2452)
		risk→HSI → DAX → DJI → DAX(t = 2326)		risk→HSI → DAX → IXI → RTS(t = 2485)
		risk→HSI → DAX → IXI → SPX(t = 2297)		risk→HSI → IBO → RTS(t = 2595)
		risk→HSI → IBO → SPX(t = 2444)		
Infected by Europe		risk→HSI → DAX → SPX(t = 2231)	risk→HSI → DAX → SH(t = 3079)	risk→HSI → FTS → RTS(t = 2264)
		risk→HSI → FTS → SPX(t = 2236)	risk→HSI → CAC → SH(t = 3157)	risk→HSI → DAX → RTS(t = 2273)
		risk→HSI → CAC → SPX(t = 2240)	risk→HSI → FTS → SH(t = 3517)	risk→HSI → CAC → RTS(t = 2276)
		risk→HSI → RTS → SPX(t = 2376)		
Infected by Asia		risk→HSI → SPX(t = 2275)	risk→HSI → SZ → SH(t = 2260)	risk→HSI → RTS(t = 2156)
		risk→HSI → SEN → SPX(t = 2333)	risk→HSI → SH(t = 2266)	risk→HSI → N225 → RTS(t = 2261)
		risk→HSI → N225 → SPX(t = 2345)	risk→HSI → N225 → SH(t = 2414)	risk→HSI → KS → RTS(t = 2268)
		risk→HSI → KS → SPX(t = 2352)	risk→HSI → KS → SH(t = 2492)	risk→HSI → SEN → RTS(t = 2275)
Infected by Oceania		risk→HSI → TW → SPX(t = 2487)	risk→HSI → TW → SH(t = 2495)	risk→HSI → TW → RTS(t = 2328)
		risk→HSI → SZ → SPX(t = 2941)	risk→HSI → SEN → SH(t = 2902)	risk→HSI → SZ → RTS(t = 3148)
		risk→HSI → SZ → SH → SPX(t = 3866)		
		risk→HSI → AS→SPX(t = 2285)	risk→HSI → AS→SH(t = 2352)	risk→HSI → AS→RTS(t = 2218)

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes

are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, and key node 3 (with the corresponding times in parentheses). "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

frequency of temperature, drought, and precipitation occurrences, and their frequent study in previous literature (Lee et al., 2022; Hong et al., 2019; Bakkensen and Barrage, 2022), we treat the anomalous data for each of these three dimensions as distinct climate risks. Additionally, to provide a comprehensive representation of climate risk, we extract the first principal component from the eight dimensions of climate data, serving as aggregate climate risk. Table 1 presents the descriptive statistics of the four climate risk series.

3.2. Stock market data

In this study, we analyze data from 16 stock markets spanning five continents, as presented in Table 2. Daily closing prices for each stock index are sourced from the Wind database, covering the same period as the climate risk data. To calculate the return series for each market, we employ the following formula (2):

$$R_t^i = \ln\left(\frac{p_t^i}{p_{t-1}^i}\right) * 100 \quad (2)$$

Where R_t^i represents the return of market i on day t , p_t^i denotes the closing price of market i on day t , and p_{t-1}^i represents the closing price of market i on the previous day $t - 1$. Descriptive statistics for the return series are provided in Table 2.

3.3. Parameter setting of the model

As outlined in Section 2, the Ripple-Spreading Network Model (RSNM) requires the specification of five key parameters. Here, we detail the methods used to calculate these parameters:

- Ability to amplify risk (α_i): We estimate this parameter by considering historical market behavior, such as sensitivity to risk or leverage. Specifically, we utilize realized volatility as a proxy for the financial market's ability to amplify risk. Higher volatility indicates greater price fluctuation and, consequently, heightened risk potential. For the risk source, we set ($\alpha_0 = 0$).
- Speed of risk propagation (s_i): While this parameter does not directly impact the final outcome of the stable financial network formed after a sufficient ripple diffusion process (where "sufficient" denotes a lengthy period until no new connection between any two nodes emerges), it does influence the time required to attain a stable network. Thus, a larger value of s_i can be employed for an initial observation of the ripple diffusion process, whereas a smaller value can be adopted for a more detailed exploration of the dynamic diffusion of risk ripples. Generally, more information-efficient markets transmit risk more swiftly. Therefore, we utilize a market's information efficiency as a gauge of the speed of risk contagion. Following the approach of Morck et al. (2000) and Gul et al. (2010), we calculate the fitted coefficients $R_{i,t}^2$ by conducting a rolling regression, specifically regressing the mean of all market returns for the current period and lagged period against the return of each market. Subsequently, we compute $\ln(R_{i,t}^2/(1-R_{i,t}^2))$ to derive the stock price synchronization index. Finally, we use the inverse of this index as a proxy variable for information efficiency, which mirrors the speed of risk contagion. As for the climate risk node, we utilize the average of the financial markets' information efficiency to denote its speed of risk contagion.
- Threshold to resist risk (β_i): β_i represents the ability of the node market i to withstand risk contagion from other nodes. A market will

Table 5

The path and timing of temperature risk transmission to representative stock markets.

	SPX	DAX	SH	RTS
Total number of paths	15	12	5	15
Total number of nodes	15	13	5	16
Key node 1 (times)	SH(13)	SH(10)	SH(4)	SH(13)
Key node 2 (times)	HSI(8)	HSI(6)		HSI(10)
Key node 3 (times)	DAX(3)	DAX(2)		DAX(4)
Key node 4 (times)	RTS(2)	RTS(2)		
The first contagion	risk→SH→HSI→DAX→SPX($t = 2771$)	risk→SH→HSI→DAX($t = 2679$)	risk→SH($t = 2368$)	risk→RTS($t = 2596$)
Infected by temperature risk			risk→SH($t = 2368$)	risk→RTS($t = 2596$)
Infected by Americas	risk→SH→HSI→DAX→DJI→SPX($t = 2824$)	risk→SH→HSI→DAX→SPX→DAX($t = 2864$)		risk→SH→HSI→DAX→DJI→RTS($t = 3035$)
	risk→SH→HSI→DAX→IXI→SPX($t = 2837$)	risk→SH→HSI→DAX→IXI→DAX($t = 2882$)		risk→SH→HSI→DAX→SPX→RTS($t = 3037$)
	risk→RTS→IBO→SPX($t = 3014$)	risk→RTS→IBO→DAX($t = 3062$)		risk→SH→HSI→DAX→IXI→RTS($t = 3077$)
Infected by Europe	risk→SH→HSI→DAX→SPX($t = 2771$)			risk→RTS→IBO→RTS($t = 3165$)
	risk→SH→HSI→FTS→SPX($t = 2776$)	risk→RTS→DAX($t = 2730$)		risk→SH→HSI→FTS→RTS($t = 2847$)
	risk→SH→HSI→CAC→SPX($t = 2780$)	risk→SH→HSI→CAC→DAX($t = 2744$)	risk→RTS→SH($t = 3389$)	risk→SH→HSI→CAC→RTS($t = 2859$)
Infected by Asia	risk→RTS→SPX($t = 2816$)			risk→SH→HSI→DAX→RTS($t = 2865$)
	risk→SH→HSI→SPX($t = 2815$)	risk→SH→HSI→DAX($t = 2679$)		risk→SH→HSI→RTS($t = 2696$)
	risk→SH→SEN→SPX($t = 2854$)	risk→SH→HSI→N225→DAX($t = 2771$)	risk→SH→SZ→SH($t = 2464$)	risk→SH→SZ→RTS($t = 2895$)
Infected by Oceania	risk→SH→HSI→N225→SPX($t = 2885$)	risk→SH→HSI→N225→DAX($t = 2797$)	risk→SH→HSI→SH($t = 2806$)	risk→SH→SEN→RTS($t = 2913$)
	risk→SH→HSI→KS→SPX($t = 2892$)	risk→SH→HSI→TW→DAX($t = 2853$)	risk→SH→SEN→SH($t = 3998$)	risk→SH→HSI→KS→RTS($t = 2962$)
	risk→SH→HSI→TW→SPX($t = 3040$)	risk→SH→SZ→DAX($t = 2865$)		risk→SH→HSI→N225→RTS($t = 2970$)
Infected by Asia	risk→SH→SZ→SPX($t = 3145$)	risk→SH→DAX($t = 2914$)		risk→SH→HSI→TW→RTS($t = 3048$)
	risk→SH→SPX($t = 3613$)			
	risk→SH→AS→SPX($t = 2801$)	risk→SH→AS→DAX($t = 2725$)		risk→SH→AS→RTS($t = 2887$)

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, key node 3, and key node 4 (with the corresponding times in parentheses). "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

succumb to risk only if the energy transmitted to this node exceeds or equals its capacity to resist risk contagion. To investigate the heterogeneity of risk diffusion processes across various timescales, we employ the inverse of the risk spillover index proposed by Baruník and Krehlík (2018) to signify this parameter. This is because a market experiencing greater risk spillover effects from the system is more susceptible to risk and typically exhibits a weaker resistance to it. To compute this parameter, we construct series for each node based on their historical data. Subsequently, we calculate the spillover index $\theta_{ij}(\omega)$ following the methodology outlined by Baruník and Krehlík (2018), which quantifies the spillover effect from market j to market i at a specific timescale ω . We consider three timescales: short-term (ranging from a day to a week), medium-term (ranging from a week to a quarter), and long-term (exceeding one quarter). Finally, we derive the inverse of the risk spillover index for each timescale $\beta_{i,\omega} = \frac{1}{\sum_{j=1, j \neq i}^N \theta_{ij}(\omega)}$. Regarding the overall capacity to resist risk contagion, we compute the weighted average of the inverse risk spillover indices across the various timescales, denoted as $\beta_i = \sum_{\omega}^3 \omega \beta_{i,\omega}$, where the weights correspond to the durations of the different timescales.

- Distance between two nodes ($D(i, j)$): The parameter $D(i, j)$ signifies the distance between node i and node j . In our model, we employ the correlation between two nodes to quantify their distance. A higher correlation suggests a shorter distance, indicating a stronger connection between the nodes. Hence, we compute the inverse of the

correlation coefficient between every pair of nodes and utilize it as the measure of distance.

- Initial energy value of the risk or wave source (E_0): The parameter E_0 represents the initial energy value of the risk source in our research. It quantifies the strength of the risk and plays a pivotal role in simulating the entire process of risk diffusion. As the value of E_0 increases, the number of stable connected edges formed by the risk diffusion process also increases. When E_0 is small, no other node can be activated, resulting in no edge being formed in the risk diffusion process, and thus, the stable network's number of edges is zero. Conversely, if E_0 is extremely large, all nodes will be activated, leading to the formation of all possible edges in the risk ripple diffusion process, and the stable network's number of edges is N^2N . In these two extreme cases, all nodes have the same impact on the network. To accurately capture the dynamic process of risk diffusion, it is imperative to set a reasonable value for the initial energy (E_0). This ensures that the risk diffusion process exhibits a gradual spread throughout the network.

According to the definition and calculation method of parameters outlined above, we computed each market's ability to amplify risk (α_i), ability to resist risk (β_i , β_{i1} , β_{i2} , β_{i3}), and speed of propagating risk (s_i). Specifically, the risk source's speed is the average of all the stock markets' parameters. These parameters are presented in Table 3. Additionally, due to space constraints, we provide the distance between all the climate risks and markets in Appendix Table A1, Table A2, Table A3, and Table A4, which represent the distance of climate risk-R network,

Table 6

The path and timing of drought risk transmission to representative stock markets.

	SPX	DAX	SH	RTS
Total number of paths	16	14	7	14
Total number of nodes	15	15	6	14
Key node 1 (times)	SZ(15)	SZ(13)	SZ(6)	SZ(14)
Key node 2 (times)	HSI(12)	HSI(11)	HSI(5)	HSI(11)
Key node 3 (times)	DAX(3)	DAX(3)		DAX(3)
The first contagion	risk→SZ→HSI→DAX→SPX($t = 1499$)	risk→SZ→HSI→DAX($t = 1407$)	risk→SZ→SH($t = 1181$)	risk→SZ→HSI→RTS($t = 1424$)
Infected by drought risk	risk→SPX($t = 3797$)	risk→DAX($t = 2428$)	risk→SH($t = 1363$)	
Infected by America	risk→SZ→HSI→DAX→DJI→SPX($t = 1552$)	risk→SZ→HSI→DAX→DJI→DAX($t = 1594$)		risk→SZ→HSI→IBO→RTS($t = 1863$)
	risk→SZ→HSI→DAX→IXI→SPX($t = 1565$)	risk→SZ→HSI→DAX→IXI→DAX($t = 1610$)		risk→SZ→HSI→DAX→SPX→RTS($t = 2741$)
	risk→SZ→HSI→IBO→SPX($t = 1712$)	risk→SZ→HSI→IBO→DAX($t = 1760$)		risk→SZ→HSI→DAX→IXI→RTS($t = 2774$)
	risk→SZ→HSI→DAX→SPX($t = 1499$)			
Infected by Europe	risk→SZ→HSI→FTS→SPX($t = 1504$)	risk→SZ→HSI→CAC→DAX($t = 1472$)	risk→SZ→HSI→DAX→SH($t = 3248$)	risk→SZ→HSI→FTS→RTS($t = 1532$)
	risk→SZ→HSI→CAC→SPX($t = 1508$)	risk→SZ→HSI→RTS→DAX($t = 1558$)	risk→SZ→HSI→FTS→SH($t = 3270$)	risk→SZ→HSI→DAX→RTS($t = 1541$)
	risk→SZ→HSI→RTS→SPX($t = 1644$)		risk→SZ→HSI→CAC→SH($t = 3326$)	risk→SZ→HSI→CAC→RTS($t = 1544$)
	risk→SZ→HSI→SPX($t = 1543$)	risk→SZ→HSI→DAX($t = 1407$)		risk→SZ→HSI→RTS($t = 1424$)
Infected by Asia	risk→SZ→HSI→SEN→SPX($t = 1601$)	risk→SZ→HSI→N225→DAX($t = 1499$)		risk→SZ→HSI→N225→RTS($t = 1529$)
	risk→SZ→HSI→N225→SPX($t = 1613$)	risk→SZ→HSI→KS→DAX($t = 1526$)	risk→SZ→SH($t = 1181$)	risk→SZ→HSI→KS→RTS($t = 1536$)
	risk→SZ→HSI→KS→SPX($t = 1620$)	risk→SZ→HSI→SEN→DAX($t = 1544$)	risk→SZ→HSI→SH($t = 1534$)	risk→SZ→HSI→SEN→RTS($t = 1543$)
	risk→SZ→HSI→TW→SPX($t = 1755$)	risk→SZ→HSI→TW→DAX($t = 1581$)	risk→SZ→HSI→N225→SH($t = 1686$)	risk→SZ→HSI→TW→RTS($t = 1596$)
Infected by Oceania	risk→SZ→SPX($t = 1862$)	risk→SZ→SH→DAX($t = 1728$)		risk→SZ→RTS($t = 1612$)
	risk→SZ→SH→SPX($t = 2427$)			risk→SZ→SH→RTS($t = 1710$)
	risk→SZ→AS→SPX($t = 1546$)	risk→SZ→AS→DAX($t = 1470$)		risk→SZ→AS→RTS($t = 1479$)

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, and key node 3 (with the corresponding times in parentheses). "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

temperature risk-R network, drought risk-R network, and precipitation risk-R network, respectively.

Next, we delve into the selection of the initial wave source energy (E_0). Through the construction of the RSNM model, we recognize that the parameter E_0 is crucial in determining whether the risk diffusion process occurs. When the initial wave source energy is too low, there is no risk diffusion phenomenon, resulting in a network with no connected edges, making it impossible to analyze the risk diffusion process of climate risks to stock markets. Therefore, it is essential to identify an appropriate energy value that can initiate the risk diffusion simulation and yield a complex network with sufficient contiguous edges for analyzing the contagion process.

To achieve this, we incrementally increased the initial wave source energy value and allowed the risk diffusion process to spread sufficiently until a stable network was formed. The relationship between the initial wave source energy value (E_0) and the total edges of the stable network (N) is depicted in Fig. 2. This figure illustrates the relationship of the whole climate risk, the temperature risk, the drought risk, and the precipitation risk to the stock markets' return series, denoted by solid, dash-dot, dashed, and dotted lines, respectively (climate risk-R, temperature risk-R, drought risk-R, and precipitation risk-R). It is observed that the total edges of the stable network increase with the initial wave source energy value.

Since our objective is to analyze the dynamic risk diffusion process of

the climate risks to the stock markets, it is imperative to ensure that the stable network has a sufficient number of edges. Therefore, we chose E_0 as 20,000 for all four climate risk-R, temperature risk-R, drought risk-R, and precipitation risk-R networks. Although the N under this value is not very close to the fully connected network ($17 \times 16 = 272$ connected edges), it is adequate for analyzing the dynamic risk diffusion process. Moreover, the N has exhibited a convergent trend, implying that further increases in E_0 have little effect on the increase of N , and may even overlook some subtle propagation processes.

4. Empirical analysis

4.1. Analysis from a time perspective

We initiate our analysis by examining the dynamic impact of climate risks on global stock markets through a temporal lens. Fig. 3 illustrates the progression of connected edges over time for each of the four climate risks. A consistent pattern emerges across all four lines: initially, the network remains edgeless, indicating no risk contagion. Subsequently, after the onset of risk transmission, the number of edges rises rapidly. However, as risk propagation reaches a certain threshold, the rate of diffusion begins to decelerate. This suggests that while the spread of climate risk is gradual, its transmission to individual stock markets prompts a swift response from the entire stock system, evidenced by a

Table 7

The path and timing of precipitation transmission to representative stock markets.

	SPX	DAX	SH	RTS
Total number of paths	16	14	5	15
Total number of nodes	15	15	4	15
Key node 1 (times)	SZ(15)	SZ(13)	SZ(4)	SZ(15)
Key node 2 (times)	HSI(12)	HSI(11)	HSI(3)	HSI(12)
Key node 3 (times)	DAX(3)	DAX(3)		DAX(4)
The first contagion	risk→SZ → HSI → DAX → SPX(t = 1615)	risk→SZ → HSI → DAX(t = 1523)	risk→SZ → SH(t = 1297)	risk→SZ → HSI → RTS(t = 1540)
Infected by precipitation risk	risk→SPX(t = 2831)	risk→DAX(t = 2734)	risk→SH(t = 1680)	
Infected by America		risk→SZ → HSI → DAX → SPX → DAX(t = 1708)		risk→SZ → HSI → IBO → RTS(t = 2173)
	risk→SZ → HSI → DAX → DJI → SPX (t = 1668)	risk→SZ → HSI → DAX → DJI → DAX(t = 1710)		risk→SZ → HSI → DAX → IXI → RTS (t = 2749)
	risk→SZ → HSI → DAX → IXI → SPX (t = 1681)	risk→SZ → HSI → DAX → IXI → DAX(t = 1726)		risk→SZ → HSI → DAX → SPX → RTS(t = 2782)
	risk→SZ → HSI → IBO → SPX(t = 1828)	risk→SZ → HSI → IBO → DAX(t = 1876)		risk→SZ → HSI → DAX → DJI → RTS (t = 2787)
Infected by Europe				risk→SZ → HSI → FTS → RTS(t = 1648)
	risk→SZ → HSI → FTS → SPX(t = 1620)	risk→SZ → HSI → CAC → DAX(t = 1588)	risk→SZ → HSI → DAX → SH(t = 3554)	risk→SZ → HSI → DAX → RTS(t = 1657)
	risk→SZ → HSI → CAC → SPX(t = 1624)	risk→SZ → HSI → RTS → DAX(t = 1674)	risk→SZ → HSI → CAC → SH(t = 3632)	risk→SZ → HSI → CAC → RTS(t = 1660)
	risk→SZ → HSI → RTS → SPX(t = 1760)			
Infected by Asia	risk→SZ → HSI → SPX(t = 1659)	risk→SZ → HSI → DAX(t = 1523)		risk→SZ → HSI → RTS(t = 1540)
	risk→SZ → HSI → SEN → SPX(t = 1717)	risk→SZ → HSI → N225 → DAX(t = 1615)		risk→SZ → HSI → N225 → RTS(t = 1645)
	risk→SZ → HSI → N225 → SPX(t = 1729)	risk→SZ → HSI → KS → DAX(t = 1642)	risk→SZ → SH(t = 1297)	risk→SZ → HSI → KS → RTS(t = 1652)
	risk→SZ → HSI → KS → SPX(t = 1736)	risk→SZ → HSI → SEN → DAX(t = 1660)	risk→SZ → HSI → SH(t = 1650)	risk→SZ → HSI → SEN → RTS(t = 1659)
	risk→SZ → HSI → TW → SPX(t = 1871)	risk→SZ → HSI → TW → DAX(t = 1697)		risk→SZ → HSI → TW → RTS(t = 1714)
	risk→SZ → SPX(t = 1978)	risk→SZ → SH → DAX(t = 1844)		risk→SZ → RTS(t = 1728)
	risk→SZ →			risk→SZ →

Table 7 (continued)

	SPX	DAX	SH	RTS
	SH → SPX(t = 2543)			SH → RTS(t = 1826)
Infected by Oceania	risk→SZ → AS→SPX(t = 1662)	risk→SZ → AS→DAX(t = 1586)		risk→SZ → AS→RTS(t = 1595)

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, and key node 3 (with the corresponding times in parentheses). "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

sharp increase in edge count. The diminishing growth rate of edges implies an enhanced capacity of financial markets to absorb and manage climate risk.

Examining the specific patterns for each climate risk in Fig. 3 reveals distinctive characteristics. The solid line representing overall climate risk exhibits edges at $t = 2000$, signaling the commencement of risk contagion, with edge growth gradually increasing from $t = 2500$. Similarly, the temperature risk (dash-dot line) shows edges at $t = 2500$, with slower growth observed post- $t = 3000$. In contrast, the dashed line depicting drought risk displays edges at $t = 1400$, with slow growth initiating at $t = 1800$. Likewise, the precipitation risk (dotted line) becomes contiguous at $t = 1500$, with edge growth commencing at $t = 1900$. These observations indicate variations in the speed of risk contagion among the four climate risks, with drought risk propagating the fastest, followed by precipitation risk, and temperature risk exhibiting the slowest spread. This discrepancy may be attributed to the immediate and direct impact of drought and precipitation on economic activities, compared to the more gradual effects of temperature changes associated with long-term climate change. Although temperature fluctuations also exert a significant influence on ecosystems and societies, the immediate repercussions of drought and precipitation risks often garner more attention due to their direct impact on livelihoods and societal well-being.

In summary, these findings offer valuable insights into the dynamic transmission of risk from various climate hazards to global stock markets, underscoring differences in their propagation speed and implications for financial systems.

4.2. Analysis from a space perspective

In this section, we delve into the spatial dynamics of climate risk transmission to global stock markets. We select pivotal moments from the transmission processes of the four climate risks, encompassing the initial arrival of climate risk to different continents and the full exposure of stock markets within continents. Figs. 4 to 7 depict the contagion paths of the four climate risks to various continent or country markets.

Fig. 4 provides a visual representation of the typical moments' network depicting the impact of overall climate risk on global stock markets. The analysis reveals a sequential transmission pattern, with climate risk initially propagating to Asian markets (HSI), followed by Oceania, Europe, and ultimately North and South America. Notably, all continents experience the initial impact of climate risk through transmission from Asian stock markets, except for North America, which first encounters risk transmission via Europe. This suggests that Asian stock markets are most promptly affected by overall climate risk, indicating relatively lower resilience to such risks. Subsequently, post-impact, Asian markets emerge as secondary sources of climate risk contagion, transmitting risk to other continents.

In detail, Fig. 4 demonstrates the chronological progression of

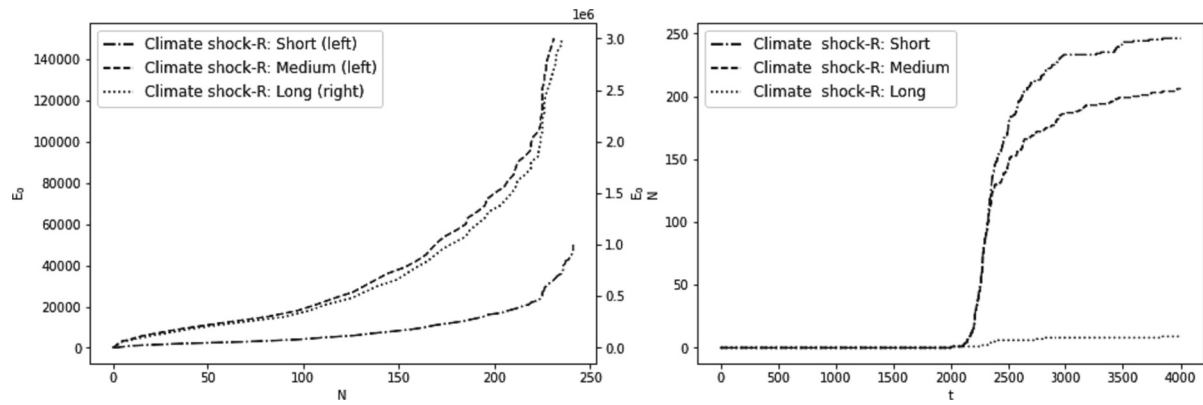


Fig. 8. Dynamic ripple diffusion process based on overall climate risk-R: three timescales.

Notes: This figure illustrates the comparison of short-, medium-, and long-timescales of the overall climate risk to stock markets' returns. E_0 represents the initial wave source energy value, while N denotes the total edges of the stable network. t indicates the time for each climate risk to transmit. The E_0 for the short- and medium-timescales are indicated by the primary axis on the left, and the results for the long term are shown by the secondary axis on the right in the left subplot.

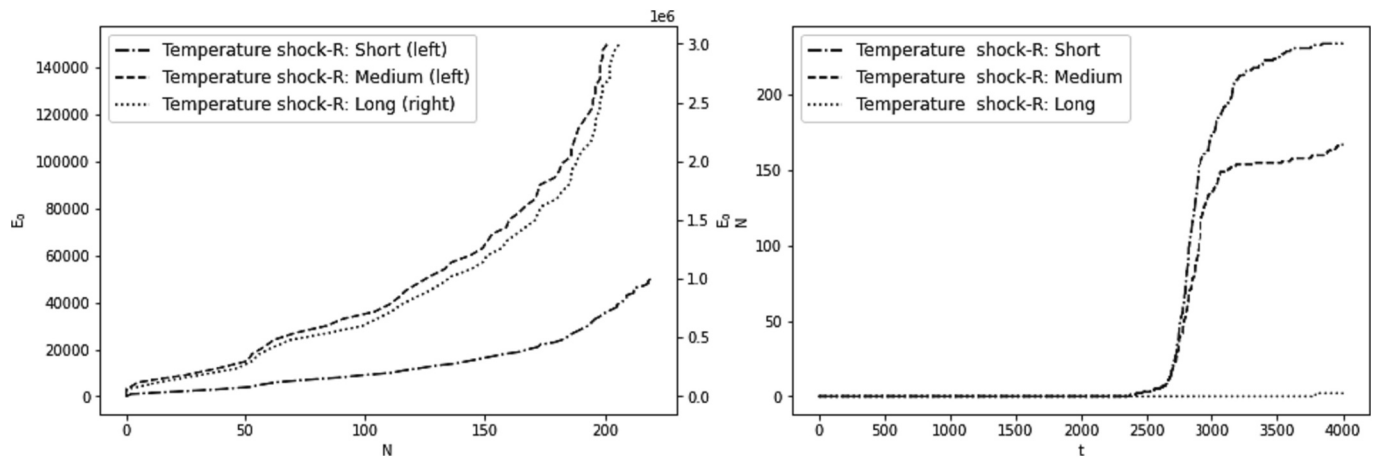


Fig. 9. Dynamic ripple diffusion process based on temperature risk-R: three timescales.

Notes: This figure compares the short-, medium-, and long-timescales of the temperature risk to stock markets' returns. E_0 represents the initial wave source energy value, while N denotes the total edges of the stable network. t indicates the time for each climate risk to transmit. The E_0 for the short- and medium-timescales are indicated by the primary axis on the left, and the results for the long term are shown by the secondary axis on the right in the left subplot.

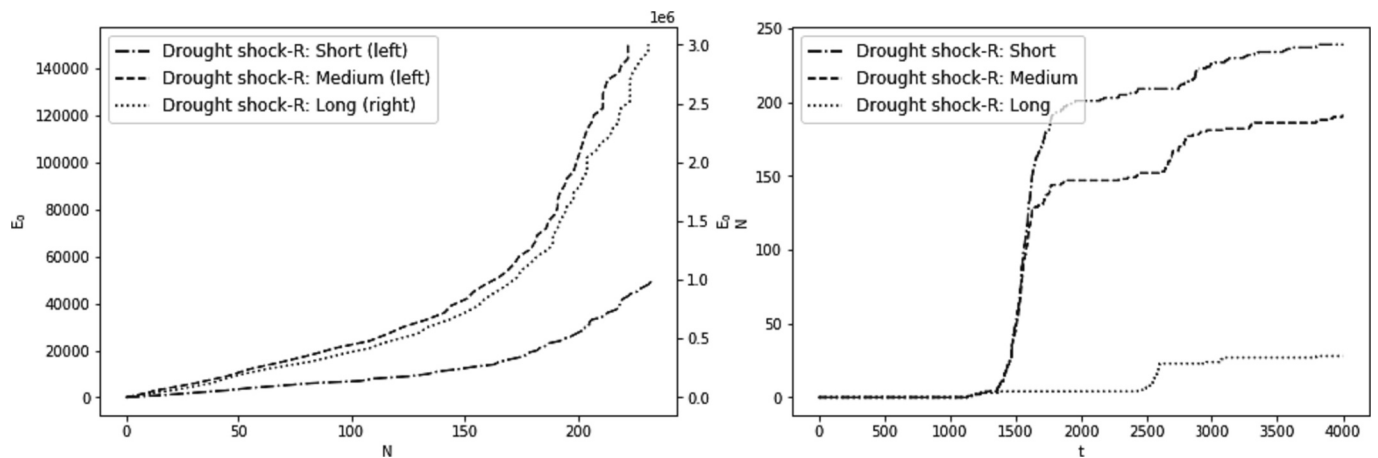


Fig. 10. Dynamic ripple diffusion process based on drought risk-R: three timescales.

Notes: This figure illustrates the comparison of short-, medium-, and long-timescales of the drought risk to stock markets' returns. E_0 represents the initial wave source energy value, while N denotes the total edges of the stable network. t indicates the time for each climate risk to transmit. The E_0 for the short- and medium-timescales are indicated by the primary axis on the left, and the results for the long term are shown by the secondary axis on the right in the left subplot.

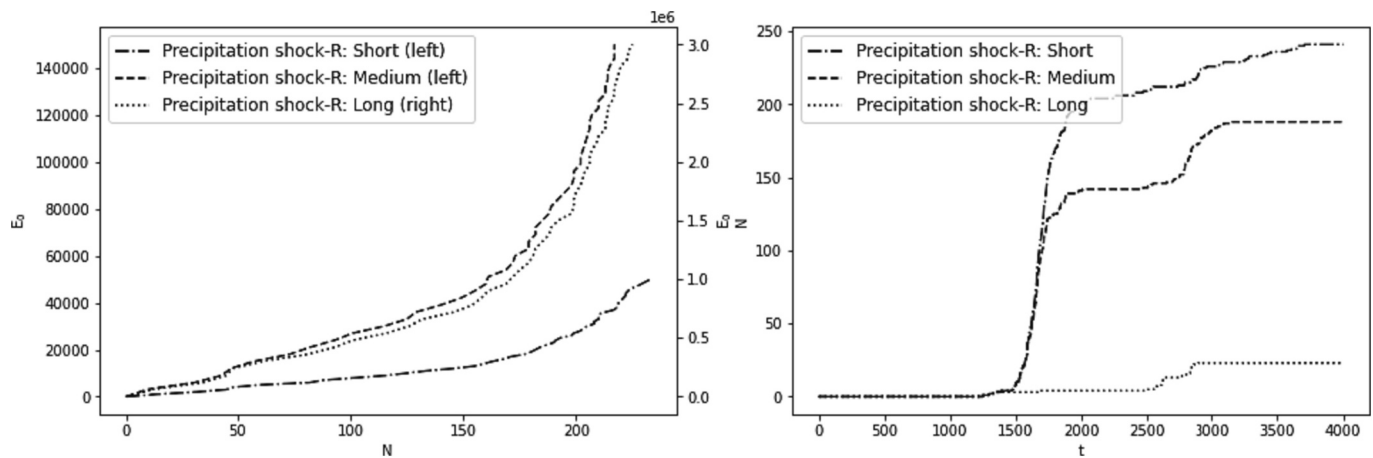


Fig. 11. Dynamic ripple diffusion process based on precipitation risk-R: three timescales.

Notes: This figure compares the short-, medium-, and long-timescales of the precipitation risk to stock markets' returns. E_0 represents the initial wave source energy value, while N denotes the total edges of the stable network. t indicates the time for each climate risk to transmit. The E_0 for the short- and medium-timescales are indicated by the primary axis on the left, and the results for the long term are shown by the secondary axis on the right in the left subplot.

climate risk transmission. Initially, at $t = 2003$ (Fig. 4(1)), the climate risk reaches the HSI market. Following a time interval of $\Delta t = 99$, the risk spreads to the Australian market (Fig. 4(2)). By $t = 2139$, DAX and FTS markets in Europe are affected indirectly through transmission from the HSI market (Fig. 4(3)). Concurrently, risk begins to disseminate within Asia, reaching the KS and N225 markets. Subsequently, all European markets are impacted by $t = 2156$ (Fig. 4(4)), and most Asian markets, except for SH and SZ, are infected (Fig. 4(5)). The Chinese mainland market experienced its first contagion at $t = 2211$ (Fig. 4(6)), followed by North American markets at $t = 2260$ (Fig. 4(7)). Eventually, South American markets are affected, accompanied by extensive contagion within and between continents (Figs. 4(10–12)).

Fig. 5 provides a visual representation of the typical moments' network illustrating the impact of temperature risk on global stock markets. The analysis reveals a sequential transmission pattern, with temperature risk initially propagating to Asian markets (SH), followed by Europe, Oceania, and ultimately North and South America. Similar to the pattern observed in Fig. 4, temperature risk predominantly originates from Asia, indicating the heightened vulnerability of Asian stock markets to temperature risk compared to other regions. This underscores the weaker capacity of Asian markets to withstand and absorb temperature risk relative to their counterparts.

In detail, Fig. 5 delineates the chronological progression of temperature risk transmission. Initially, at $t = 2368$ (Fig. 5(1)), temperature risk transmits to the Asian SH market, followed by contagion to the SZ market after a time interval of $\Delta t = 48$ (Fig. 5(2)). Subsequently, contagion spreads from the SH market to other Asian markets, commencing with the HSI market (Fig. 5(3)). The European RFS market is first impacted by temperature risk at $t = 2618$ (Fig. 5(4)), followed by the addition of a new connected edge from the SH market to the Australian market at $t = 2618$ (Fig. 5(5)). Concurrently, temperature risk propagates to other European markets, while the HSI market transmits risk to the mainland Chinese and N225 markets (Fig. 5(6)). By $t = 2691$, all Asian markets have been infected (Fig. 5(7)), accompanied by cross-continental contagion between Oceania and Asia. Subsequently, transmission occurs from the mainland Chinese market to all other Asian markets by $t = 2701$ (Fig. 5(8)). The North American market is first affected by temperature risk at $t = 2701$, transmitted through the German DAX market (Fig. 5(9)), with all North American markets contaminated by $t = 2701$ (Fig. 5(10)). Finally, contamination of the IBO market in South America by the Russian RTS market is observed (Fig. 5(11)), along with extensive contagion within and between continents (Fig. 5(12)).

Fig. 6 illustrates the networks depicting the impact of drought risk on

global stock markets. The analysis reveals a sequential transmission pattern, with drought risk first propagating to Asian markets (SZ), followed by Oceania, Europe, and ultimately North and South America. Similar to the patterns observed in previous figures, drought risk predominantly emanates from Asia, underscoring the vulnerability of Asian stock markets to climate risks.

In terms of the specific transmission process, Fig. 6(1) illustrates that drought risk initially transmits to the SZ stock market in China at $t = 1133$. Subsequently, after a time interval of 48, the SZ market transmits drought risk to the SH market (Fig. 6(2)). Contagion between the SH and SZ markets is observed in Fig. 6(3), with the SZ market also exhibiting a connection to the HSI market. Furthermore, Fig. 6(4) indicates the first impact of drought risk on the Australian market, transmitted through the SZ market. At $t = 1407$, as shown in Fig. 6(5), the European market is initially affected by drought risk transmitted through the HSI market, accompanied by cross-contagion within Asia. Fig. 6(6) demonstrates that all European markets have now been infected with drought risk, primarily through the HSI stock market. By $t = 1438$, Fig. 6(7) illustrates the contamination of all Asian markets. Additionally, Fig. 6(8) depicts the transmission of drought risk from the mainland Chinese market to other Asian markets. The first transmission of drought risk through the German DAX stock market to both the DJI and SPX stock markets in North America is evident in Fig. 6(9). Fig. 6(10) displays the contagion of all North American stock markets, with risk transmission not only from the German DAX market but also from France's CAC market and the UK FTS market in Europe to North American stock markets. Fig. 6(11) illustrates the initial exposure of South American stock markets to risk contagion. Finally, Fig. 6(12) represents a more complex risk contagion both within and between continents.

Fig. 7 illustrates the networks depicting the impact of precipitation risk on global stock markets. The analysis reveals a sequential transmission pattern, with precipitation risk first propagating to Asian markets (SZ), followed by Oceania, Europe, and ultimately North and South America. Similar to previous figures, precipitation risk predominantly emanates from the SZ market in Asia, underscoring the vulnerability of Asian equity markets to climate risks.

In terms of the specific transmission process, Fig. 7(1) reveals that precipitation risk is initially transmitted to the SZ stock market at $t = 1249$. Subsequently, after a time interval of 48, the SZ stock market transmits precipitation risk to the SH stock market (Fig. 7(2)). Fig. 7(3) illustrates the transmission of precipitation risk from the SZ stock market to the HSI stock market. Furthermore, Fig. 7(4) shows that the Australian market is first exposed to precipitation risk through the SZ stock market, while the SH also transmits risk to the HSI market during this

Table 8

Comparison of the path and time of short-, medium-, and long-timescales: overall climate risk.

		SPX	DAX	SH	RTS
Total number of paths	Short	15	14	12	14
	Medium	14	14	4	13
	Long	0	2	0	0
Total number of nodes	Short	15	15	11	14
	Medium	14	15	3	13
	Long	0	2	0	0
Key node 1 (times)	Short	HSI(15)	HSI(14)	HSI(11)	HSI(14)
	Medium	HSI(14)	HSI(14)	HSI(3)	HSI(13)
	Long				
Key node 2 (times)	Short	DAX(3)	DAX(3)		DAX(3)
	Medium	DAX(3)	DAX(3)		DAX(3)
	Long				
Key node 3 (times)	Short	SZ(2)	SZ(2)		SZ(2)
	Medium		SZ(2)		
	Long				
The first contagion	Short	risk→HSI → DAX → SPX(t = 2231)	risk→HSI → DAX(t = 2139)	risk→HSI → SZ → SH(t = 2260)	risk→HSI → RTS(t = 2156)
	Medium	risk→HSI → DAX → SPX(t = 2231)	risk→HSI → DAX(t = 2139)	risk→HSI → SZ → SH(t = 2260)	risk→HSI → RTS(t = 2156)
	Long		risk→DAX(t = 2259)		
Infected by overall climate risk	Short			risk→SH(t = 2621)	
	Medium			risk→SH(t = 2621)	
	Long				
Infected by America	Short	risk→HSI → DAX → DJI → SPX(t = 2284) risk→HSI → DAX → IXI → SPX(t = 2297) risk→HSI → IBO → SPX(t = 2444)	risk→HSI → DAX → SPX → DAX(t = 2324) risk→HSI → DAX → DJI → DAX(t = 2326) risk→HSI → DAX → IXI → DAX(t = 2342) risk→HSI → IBO → DAX(t = 2492)		risk→HSI → DAX → SPX → RTS(t = 2452) risk→HSI → DAX → IXI → RTS(t = 2485) risk→HSI → IBO → RTS(t = 2595)
	Medium	risk→HSI → DAX → DJI → SPX(t = 2284) risk→HSI → DAX → IXI → SPX(t = 2297) risk→HSI → IBO → SPX(t = 2444)	risk→HSI → DAX → DJI → DAX(t = 2326) risk→HSI → DAX → IXI → DAX(t = 2342) risk→HSI → IBO → DAX(t = 2492)		risk→HSI → DAX → SPX → RTS(t = 2572) risk→HSI → DAX → IXI → RTS(t = 2605) risk→HSI → IBO → RTS(t = 2725)
	Long	risk→HSI → DAX → SPX(t = 2231) risk→HSI → FTS → SPX(t = 2236) risk→HSI → CAC → SPX(t = 2240) risk→HSI → RTS → SPX(t = 2376)	risk→HSI → CAC → DAX(t = 2204) risk→HSI → RTS → DAX(t = 2290)	risk→HSI → FTS → SH(t = 2916) risk→HSI → RTS → SH(t = 2949) risk→HSI → DAX → SH(t = 2959) risk→HSI → CAC → SH(t = 2984)	risk→HSI → FTS → RTS(t = 2264) risk→HSI → DAX → RTS(t = 2273) risk→HSI → CAC → RTS(t = 2276)
Infected by Europe	Short	risk→HSI → DAX → SPX(t = 2231) risk→HSI → FTS → SPX(t = 2236) risk→HSI → CAC → SPX(t = 2240) risk→HSI → RTS → SPX(t = 2376)	risk→HSI → CAC → DAX(t = 2204) risk→HSI → RTS → DAX(t = 2290)		risk→HSI → FTS → RTS(t = 2264) risk→HSI → DAX → RTS(t = 2273) risk→HSI → CAC → RTS(t = 2276)
	Medium	risk→HSI → DAX → SPX(t = 2231) risk→HSI → FTS → SPX(t = 2236) risk→HSI → CAC → SPX(t = 2240) risk→HSI → RTS → SPX(t = 2376)	risk→HSI → CAC → DAX(t = 2204) risk→HSI → RTS → DAX(t = 2290)		risk→HSI → FTS → RTS(t = 2264) risk→HSI → DAX → RTS(t = 2273) risk→HSI → CAC → RTS(t = 2276)
	Long	risk→HSI → SPX(t = 2275) risk→HSI → SEN → SPX(t = 2333) risk→HSI → N225 → SPX(t = 2345) risk→HSI → KS → SPX(t = 2352) risk→HSI → TW → SPX(t = 2487) risk→HSI → SZ → SPX(t = 2941) risk→HSI → SZ → SH → SPX(t = 3506)	risk→HSI → DAX(t = 2139) risk→HSI → N225 → DAX(t = 2231) risk→HSI → KS → DAX(t = 2258) risk→HSI → SEN → DAX(t = 2276) risk→HSI → TW → DAX(t = 2313) risk→HSI → SZ → DAX(t = 2661) risk→HSI → SZ → SH → DAX(t = 2807)	risk→HSI → SZ → SH(t = 2260) risk→HSI → SH(t = 2266) risk→HSI → SEN → SH(t = 2412) risk→HSI → N225 → SH(t = 2414) risk→HSI → KS → SH(t = 2492) risk→HSI → TW → SH(t = 2495)	risk→HSI → RTS(t = 2156) risk→HSI → N225 → RTS(t = 2261) risk→HSI → KS → RTS(t = 2268) risk→HSI → SEN → RTS(t = 2275) risk→HSI → TW → RTS(t = 2328) risk→HSI → SZ → RTS(t = 2691) risk→HSI → SZ → SH → RTS(t = 2789)
Infected by Asia	Short	risk→HSI → SPX(t = 2275) risk→HSI → SEN → SPX(t = 2333) risk→HSI → N225 → SPX(t = 2345) risk→HSI → KS → SPX(t = 2352) risk→HSI → TW → SPX(t = 2487) risk→HSI → SZ → SPX(t = 2941) risk→HSI → SZ → SH → SPX(t = 3506)	risk→HSI → DAX(t = 2139) risk→HSI → N225 → DAX(t = 2231) risk→HSI → KS → DAX(t = 2258) risk→HSI → SEN → DAX(t = 2276) risk→HSI → TW → DAX(t = 2313) risk→HSI → SZ → DAX(t = 2661) risk→HSI → SZ → SH → DAX(t = 2807)	risk→HSI → SZ → SH(t = 2260) risk→HSI → SH(t = 2266) risk→HSI → SEN → SH(t = 2412)	risk→HSI → RTS(t = 2156) risk→HSI → N225 → RTS(t = 2261) risk→HSI → KS → RTS(t = 2268) risk→HSI → SEN → RTS(t = 2275) risk→HSI → TW → RTS(t = 2328) risk→HSI → SZ → RTS(t = 2691) risk→HSI → SZ → SH → RTS(t = 2789)
	Medium	risk→HSI → SPX(t = 2275) risk→HSI → SEN → SPX(t = 2333) risk→HSI → N225 → SPX(t = 2345)	risk→HSI → DAX(t = 2139) risk→HSI → N225 → DAX(t = 2231) risk→HSI → KS → DAX(t = 2258) risk→HSI → SEN → DAX(t = 2276)	risk→HSI → SZ → SH(t = 2260) risk→HSI → SH(t = 2266) risk→HSI → SEN → SH(t = 2412)	risk→HSI → RTS(t = 2156) risk→HSI → N225 → RTS(t = 2261) risk→HSI → KS → RTS(t = 2268) risk→HSI → SEN → RTS(t = 2275)
	Long	risk→HSI → SPX(t = 2275) risk→HSI → SEN → SPX(t = 2333) risk→HSI → N225 → SPX(t = 2345)	risk→HSI → DAX(t = 2139) risk→HSI → N225 → DAX(t = 2231) risk→HSI → KS → DAX(t = 2258) risk→HSI → SEN → DAX(t = 2276)	risk→HSI → SZ → SH(t = 2260) risk→HSI → SH(t = 2266) risk→HSI → SEN → SH(t = 2412)	risk→HSI → RTS(t = 2156) risk→HSI → N225 → RTS(t = 2261) risk→HSI → KS → RTS(t = 2268) risk→HSI → SEN → RTS(t = 2275)

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Table 8 (continued)

		SPX	DAX	SH	RTS
		risk→HSI → KS → SPX($t = 2352$)	2276)		2275)
		risk→HSI → TW → SPX($t = 2487$)	risk→HSI → TW → DAX($t = 2313$)		risk→HSI → TW → RTS($t = 2328$)
		risk→HSI → SZ → SPX($t = 3398$)	risk→HSI → SZ → DAX($t = 3118$)		risk→HSI → SZ → RTS($t = 3300$)
			risk→HSI → SZ → SH → DAX($t = 3167$)		
	Long				
	Short	risk→HSI → AS→SPX($t = 2285$)	risk→HSI → AS→DAX($t = 2209$)	risk→HSI → AS→SH($t = 2352$)	risk→HSI → AS→RTS($t = 2218$)
Infected by Oceania	Medium	risk→HSI → AS→SPX($t = 2285$)	risk→HSI → AS→DAX($t = 2209$)		risk→HSI → AS→RTS($t = 2218$)
	Long				

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, and key node 3 (with the corresponding times in parentheses). "short," "media," and "long" represent the short-, medium-, and long- timescales. "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

period. At $t = 1523$, Fig. 7(5) demonstrates the first transmission of precipitation risk to European markets via the HSI market, reaching both the German and UK markets simultaneously. Fig. 7(6) indicates that all European markets are infected, with the HSI stock market serving as the bridge of the precipitation risk contagion. Fig. 7(7) confirms that all Asian stock markets have been affected. Additionally, Fig. 7(8) shows that the mainland China market has transmitted risk to all other Asian stock markets. The first transmission of precipitation risk to North American stock markets via the German DAX market is shown in Fig. 7(9). Fig. 7(10) demonstrates that all North American stock markets have been exposed to precipitation risk. Fig. 7(11) illustrates the initial transmission of risk from the HSI stock market to South American stock markets. Finally, Fig. 7(12) displays the risk contagion within and between continents.

In summary, these spatial analyses provide invaluable insights into the sequential transmission of climate risks to global stock markets, underscoring the critical role of Asian markets as primary vectors of contagion and highlighting vulnerabilities across different regions.

4.3. Analysis from typical paths and time perspective

The preceding investigation elucidates the influence of four climate risks on global stock markets, examining both temporal and spatial dimensions. However, it is imperative to grasp how these risks are specifically transmitted to individual stock markets and the timing of such occurrences. This section synthesizes the paths and timing of each risk's transmission to financial markets, essential for risk regulation and management. Due to constraints, we focus on four representative markets: SPX in the US, DAX in Germany, SH in China, and RTS in Russia.

Table 4 delineates the paths and timing of the transmission of aggregate climate risks to pivotal financial markets. Notably, there are 15 transmission paths to the SPX during the risk contagion process, involving 15 nodes. Among these nodes, HSI emerges 15 times, DAX 3 times, and SZ 2 times, underscoring their pivotal roles as transmission nodes. The paths originate from diverse regions: three from the Americas, four from Europe, seven from Asia, and one from Oceania. Notably, the swiftest path from Germany (DAX) in Europe to SPX occurs at $t = 2231$. Interestingly, there is no direct transmission path from the risk source to SPX, suggesting indirect exposure to climate risk from other financial markets.

During the risk contagion process, 14 transmission paths lead to the DAX market, involving 15 nodes. Key nodes such as HSI, DAX, and SZ appear frequently. These paths span regions, with four from the Americas, two from Europe, seven from Asia, and one from Oceania. The earliest transmission to DAX occurs through the HSI path from Asia, observed at $t = 2139$. Similar to SPX, there is no direct path from the risk source to the DAX market, necessitating consideration of when other markets, particularly the HSI market, are affected by climate risk in risk

management strategies.

Regarding the SH market, 11 transmission paths involve 10 nodes, with HSI appearing prominently. One path originates from the risk source, three from Europe, six from Asia, and one from Oceania. The earliest transmission is from the SZ market. Although there is a direct transmission path from the risk source to the SH market, indirect transmission is faster. No pathways from the Americas suggest a focus on Asia, Oceania, and Europe for climate risk prevention efforts, with particular attention to the HSI market.

There are 13 transmission pathways to the RTS market, with HSI appearing prominently in all paths. These paths originate from various regions: three from the Americas, three from Europe, six from Asia, and one from Oceania. The earliest path is from the HSI market at $t = 2156$. Notably, the RTS market is not directly transmitted from the risk source, necessitating vigilance in monitoring financial markets, especially the HSI and DAX markets.

Comparatively, SPX exhibits the highest number of transmission paths, followed by DAX, RTS, and SH. DAX experiences the fastest transmission of climate risk, followed by RTS, SPX, and SH. Only the SH market has a direct transmission pathway from the climate risk source. HSI frequently appears in transmission pathways across all representative markets, underscoring its importance in climate risk prevention and control.

Table 5 summarizes the pathways and timing of temperature risk transmission to key financial markets. Notably, there are 15 transmission paths to the SPX market during the risk contagion process, involving 15 nodes. Key nodes such as SH, HSI, DAX, and RTS play significant roles. These paths span regions, with three from the Americas, four from Europe, seven from Asia, and one from Oceania. The earliest transmission to the SPX market originates from the German DAX market at $t = 2771$. Similar to previous findings, there are no direct paths from the risk source to SPX, emphasizing indirect exposure to temperature risk from other markets.

Throughout the temperature risk contagion process, 12 transmission paths lead to the DAX market, involving 13 nodes. Key nodes such as SH, HSI, DAX, and RTS are pivotal. These paths originate from diverse regions, with three from the Americas, two from Europe, six from Asia, and one from Oceania. The earliest transmission to DAX occurs through the HSI market at $t = 2679$. Interestingly, DAX itself serves as a transmission node, indicating bidirectional influence between DAX and other markets in temperature risk transmission.

Regarding the SH market, five transmission paths involve five nodes, with SH appearing prominently. One path originates from the risk source, one from European RTS, and three from Asia. The earliest transmission to the SH market is a direct path from the risk source at $t = 2368$. Similar to previous findings, no paths are transmitted from the Americas. However, the direct transmission path from the risk source is the earliest among all paths.

Table 9

Comparison of the path and time of short-, medium-, and long-timescales: temperature risk.

		SPX	DAX	SH	RTS
Total number of paths	Short	15	12	12	15
	Medium	14	13	2	7
	Long	1	0	0	0
Total number of nodes	Short	15	13	12	16
	Medium	14	14	2	7
	Long	1	0	0	0
Key node 1 (times)	Short	SH(13)	SH(10)	SH(11)	SH(13)
	Medium	SH(12)	SH(11)		SH(6)
	Long				
Key node 2 (times)	Short	HSI(8)	HSI(6)	HSI(7)	HSI(10)
	Medium	HSI(7)	HSI(6)		HSI(4)
	Long				
Key node 3 (times)	Short	DAX(3)	DAX(2)		DAX(4)
	Medium	DAX(3)	DAX(2)		
	Long				
Key node 4 (times)	Short	RTS(2)	RTS(2)		
	Medium	RTS(2)	RTS(2) SZ(2)		
	Long				
The first contagion	Short	risk→SH→HSI→DAX→SPX(t = 2771)	risk→SH→HSI→DAX(t = 2679)	risk→SH(t = 2368)	risk→RTS(t = 2596)
	Medium	risk→SH→HSI→DAX→SPX(t = 2771)	risk→SH→HSI→DAX(t = 2679)	risk→SH(t = 2368)	risk→RTS(t = 2596)
	Long	risk→IXI→SPX(t = 3820)			
Infected by temperature risk	Short			risk→SH(t = 2368)	risk→RTS(t = 2596)
	Medium			risk→SH(t = 2368)	risk→RTS(t = 2596)
	Long				
Infected by America	Short	risk→SH→HSI→DAX→DJI→SPX(t = 2824) risk→SH→HSI→DAX→IXI→SPX(t = 2837) risk→RTS→IBO→SPX(t = 3014)	risk→SH→HSI→DAX→SPX→DAX(t = 2864) risk→SH→HSI→DAX→IXI→DAX(t = 2882) risk→RTS→IBO→DAX(t = 3032)		risk→SH→HSI→DAX→DJI→RTS(t = 3035) risk→SH→HSI→DAX→SPX→RTS(t = 3037) risk→SH→HSI→DAX→IXI→RTS(t = 3077) risk→RTS→IBO→RTS(t = 3165)
	Medium	risk→SH→HSI→DAX→DJI→SPX(t = 2824) risk→SH→HSI→DAX→IXI→SPX(t = 2837) risk→RTS→IBO→SPX(t = 3014)	risk→SH→HSI→DAX→SPX→DAX(t = 2909) risk→SH→HSI→DAX→IXI→DAX(t = 2934) risk→RTS→IBO→DAX(t = 3062)		
	Long	risk→IXI→SPX(t = 3820) risk→SH→HSI→DAX→SPX(t = 2771)		risk→RTS→SH(t = 3389)	risk→SH→HSI→FTS→RTS(t = 2804)
Infected by Europe	Short	risk→SH→HSI→FTS→SPX(t = 2776) risk→SH→HSI→CAC→SPX(t = 2780) risk→RTS→SPX(t = 2816) risk→SH→HSI→DAX→SPX(t = 2771)	risk→RTS→DAX(t = 2730) risk→SH→HSI→CAC→DAX(t = 2744)	risk→FTS→SH(t = 3499) risk→DAX→SH(t = 3551) risk→CAC→SH(t = 3567)	risk→SH→HSI→DAX→RTS(t = 2813) risk→SH→HSI→CAC→RTS(t = 2816)
	Medium	risk→SH→HSI→FTS→SPX(t = 2776) risk→SH→HSI→CAC→SPX(t = 2780) risk→RTS→SPX(t = 2816)	risk→RTS→DAX(t = 2730) risk→SH→HSI→CAC→DAX(t = 2744)		risk→SH→HSI→FTS→RTS(t = 2847) risk→SH→HSI→CAC→RTS(t = 2859) risk→SH→HSI→DAX→RTS(t = 2865)
	Long				
Infected by Asia	Short	risk→SH→HSI→SPX(t = 2815) risk→SH→SEN→SPX(t = 2854) risk→SH→HSI→N225→SPX(t = 2885) risk→SH→HSI→KS→SPX(t = 2892) risk→SH→HSI→TW→SPX(t = 3040) risk→SH→SZ→SPX(t = 3145) risk→SH→SPX(t = 3613)	risk→SH→HSI→DAX(t = 2679) risk→SH→HSI→N225→DAX(t = 2771) risk→SH→SEN→DAX(t = 2797) risk→SH→HSI→TW→DAX(t = 2853) risk→SH→SZ→DAX(t = 2865) risk→SH→DAX(t = 2914)	risk→SH→SZ→SH(t = 2464) risk→SH→HSI→SH(t = 2806) risk→SH→SEN→SH(t = 3050) risk→SH→N225→SH(t = 3123) risk→SH→KS→SH(t = 3186) risk→SH→TW→SH(t = 3215)	risk→SH→HSI→RTS(t = 2696) risk→SH→SEN→RTS(t = 2796) risk→SH→HSI→N225→RTS(t = 2801) risk→SH→HSI→KS→RTS(t = 2808) risk→SH→HSI→TW→RTS(t = 2881) risk→SH→SZ→RTS(t = 2895)
	Medium	risk→SH→HSI→SPX(t = 2815) risk→SH→SEN→SPX(t = 2971) risk→SH→HSI→KS→SPX(t = 3046) risk→SH→HSI→N225→SPX(t = 3054) risk→SH→SZ→SPX(t = 3145) risk→SH→SPX(t = 3613)	risk→SH→HSI→DAX(t = 2679) risk→SH→HSI→N225→DAX(t = 2771) risk→SH→SEN→DAX(t = 2797) risk→SH→HSI→KS→DAX(t = 2809) risk→SH→SZ→DAX(t = 2865) risk→SH→SZ→TW→DAX(t = 2865)	risk→SH→SZ→SH(t = 2464)	risk→SH→HSI→RTS(t = 2696) risk→SH→SZ→RTS(t = 2895) risk→SH→SEN→RTS(t = 3861)
	Long				

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Table 9 (continued)

	SPX	DAX	SH	RTS
		2866) risk→SH → DAX(t = 2914)		
Long				
Short	risk→SH → AS→SPX(t = 2801)	risk→SH → AS→DAX(t = 2725)	risk→SH → AS→SH(t = 3021)	risk→SH → AS→RTS(t = 2734)
Infected by Oceania	Medium risk→SH → AS→SPX(t = 2954)	Long risk→SH → AS→DAX(t = 2725)		
Long				

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, key node 3, and key node 4 (with the corresponding times in parentheses). "short," "media," and "long" represent the short-, medium-, and long- timescales. "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

There are 15 transmission paths to the RTS market, covering 16 nodes, with SH, HSI, and DAX playing significant roles. These paths originate from various regions, with direct contagion from the temperature risk source occurring at $t = 2596$. Notably, this direct transmission is the earliest among all paths.

Comparatively, temperature risk transmission is more prominent in the SPX and RTS markets, with 15 paths each, followed by the DAX market, and finally the SH market. The sequence of temperature risk contagion differs from overall climate risk, with the SH market experiencing contagion first, followed by RTS, DAX, and finally SPX. Temperature risk transmission generally occurs later than overall climate risk transmission in all four representative stock markets. Additionally, given its frequent appearance in transmission paths, attention to the SH market is crucial alongside the HSI and DAX markets for effective temperature risk prevention and control.

Table 6 provides an overview of drought risk transmission pathways to representative financial markets. Throughout the contagion process, 16 paths transmit drought risk to the SPX market, involving 15 nodes. Key nodes such as SZ, HSI, and DAX feature prominently. These paths originate globally, with one directly from the risk source, and others from the Americas, Europe, Asia, and Oceania. The earliest transmission to SPX occurs from the DAX market at $t = 1499$, emphasizing the significance of indirect risks from other financial markets.

Drought risk is transmitted through 14 paths to the DAX market, involving 15 nodes. Key nodes such as SZ, HSI, and DAX play crucial roles. Notably, there exists a direct transmission path from the risk source to the DAX market, with the earliest transmission from the HSI market at $t = 1407$.

Concerning the SH market, 7 transmission paths involve 6 nodes, with SZ and HSI appearing prominently. These paths primarily originate from Europe and Asia, with no paths from the Americas or Oceania. The earliest transmission to the SH market occurs from the SZ market at $t = 1181$.

Throughout the contagion process, 14 paths transmit drought risk to the RTS market, with key nodes including SZ, HSI, and DAX. These paths originate globally, with the earliest transmission from the HSI market at $t = 1427$. Notably, there is no direct transmission from the risk source to the RTS market.

Comparatively, drought risk transmits to the SPX market through most pathways, followed by RTS, DAX, and SH. The SH market is the earliest to be affected, followed by DAX, RTS, and finally SPX. Drought risk occurs earlier than temperature risk, possibly due to the immediate impact of droughts, resulting in faster transmission to the stock market.

Table 7 outlines the pathways and timing of precipitation risk transmission to representative financial markets. There are 16 transmission paths to the SPX market, involving 15 nodes, with SZ, HSI, and DAX being notable nodes. These paths originate globally, with one directly from the risk source and others from regions including the Americas, Europe, Asia, and Oceania. The earliest path to SPX originates from the European DAX market at $t = 1615$. Although similar to drought risk findings in terms of paths and key nodes, the time of precipitation

risk reaching SPX is delayed compared to drought risk, with an earlier direct transmission from the risk source.

Throughout the contagion process, 14 pathways transmit risk to the DAX market, involving 15 nodes. Key nodes such as SZ and HSI feature prominently. The earliest pathway originates from the Asian HSI market at $t = 1523$, aligning with drought risk findings but with a later transmission to DAX.

For the SH market, 5 pathways involve 4 nodes, with SZ and HSI being prominent. The earliest transmission occurs from SZ to SH in Asia at $t = 1297$, with no involvement from America or Oceania. However, pathways from European FTS and Asian N225 are absent, and both the earliest and direct transmissions are delayed.

Regarding the RTS market, 15 paths involve 15 nodes, with SZ, HSI, and DAX being key nodes. The earliest transmission to RTS is from the HSI market at $t = 1540$. Unlike other markets, RTS lacks a direct transmission path from the precipitation risk source, necessitating close monitoring of other financial markets, particularly SZ, HSI, and DAX.

Overall, SPX receives the highest number of paths for precipitation risk transmission, followed by RTS, DAX, and SH. The sequence of transmission follows SH being the first affected, followed by DAX, RTS, and finally SPX, consistent with drought risk contagion. Precipitation risk occurrence is slightly delayed compared to drought risk but precedes temperature risk.

To sum up, the SPX has the highest number of transmission paths for climate risk among the four representative stock markets, followed by DAX, RTS, and SH. In terms of the sequence of being impacted by climate risk, DAX experiences the fastest transmission, followed by RTS, SPX, and SH markets in that order. The frequent appearance of HSI in the transmission paths of all representative markets highlights the importance of monitoring trends in the HSI market for overall climate risk prevention and control.

These findings give some insights into risk management. For overall climate risk, in addition to the HSI and DAX markets mentioned in Table 4, it is crucial to pay close attention to the SH market as it features in almost all transmission paths. Temperature risk transmission is more prominent in the SPX and RTS markets, necessitating enhanced monitoring and risk mitigation measures for these markets. Drought risk transmits to the SPX market through the most paths, indicating the need for increased regulation and preventive measures against drought risk. Precipitation risk transmission is significant in the SPX and RTS markets, with the SH market being the first to be affected, emphasizing the importance of monitoring risk in the SH market. These recommendations are intended to assist regulatory bodies and investors in better understanding the impact of climate risk on stock markets and implementing appropriate risk management and prevention measures to safeguard investor interests and financial market stability.

4.4. Comparison of short-, medium-, and long-timescales

4.4.1. The dynamic diffusion process at different timescales

Understanding how climate risks affect global stock markets at

Table 10

Comparison of the path and time of short-, medium-, and long-timescales: drought risk.

		SPX	DAX	SH	RTS
Total number of paths	Short	16	14	12	14
	Medium	16	14	3	14
	Long	6	4	2	0
Total number of nodes	Short	15	15	11	14
	Medium	15	15	2	14
	Long	5	4	1	0
Key node 1 (times)	Short	SZ(15)	SZ(13)	SZ(11)	SZ(14)
	Medium	SZ(15)	SZ(13)	SZ(2)	SZ(14)
	Long	DAX(5)	DAX(3)		
Key node 2 (times)	Short	HSI(12)	HSI(11)	HSI(9)	HSI(11)
	Medium	HSI(12)	HSI(11)		HSI(11)
	Long				
Key node 3 (times)	Short	DAX(3)	DAX(3)		DAX(3)
	Medium	DAX(3)	DAX(3)		DAX(3)
	Long				
The first contagion	Short	risk→SZ → HSI → DAX → SPX(t = 1499)	risk→SZ → HSI → DAX(t = 1407)	risk→SZ → SH(t = 1181)	risk→SZ → HSI → RTS(t = 1424)
	Medium	risk→SZ → HSI → DAX → SPX(t = 1499)	risk→SZ → HSI → DAX(t = 1407)	risk→SZ → SH(t = 1181)	risk→SZ → HSI → RTS(t = 1424)
	Long	risk→DAX → SPX(t = 2520)	risk→DAX(t = 2428)	risk→SZ → SH(t = 1181)	
Infected by drought risk	Short	risk→SPX(t = 3797)	risk→DAX(t = 2428)	risk→SH(t = 1363)	
	Medium	risk→SPX(t = 3797)	risk→DAX(t = 2428)	risk→SH(t = 1363)	
	Long	risk→SPX(t = 3797)	risk→DAX(t = 2428)	risk→SH(t = 1363)	
Infected by America	Short	risk→SZ → HSI → DAX → DJI → SPX(t = 1552)	risk→SZ → HSI → DAX → DJI → DAX(t = 1592)		risk→SZ → HSI → DAX → IXI → RTS(t = 1789)
	Short	risk→SZ → HSI → DAX → IXI → SPX(t = 1565)	risk→SZ → HSI → DAX → IXI → DAX(t = 1594)		risk→SZ → HSI → IBO → RTS(t = 1863)
	Short	risk→SZ → HSI → IBO → SPX(t = 1712)	risk→SZ → HSI → IBO → DAX(t = 1760)		risk→SZ → HSI → DAX → SPX → RTS(t = 2741)
Infected by Europe	Medium	risk→SZ → HSI → DAX → DJI → SPX(t = 1552)	risk→SZ → HSI → DAX → DJI → DAX(t = 1592)		risk→SZ → HSI → DAX → SPX → RTS(t = 2741)
	Medium	risk→SZ → HSI → DAX → IXI → SPX(t = 1565)	risk→SZ → HSI → DAX → IXI → DAX(t = 1594)		risk→SZ → HSI → DAX → IXI → RTS(t = 2774)
	Medium	risk→SZ → HSI → IBO → SPX(t = 1712)	risk→SZ → HSI → IBO → DAX(t = 1760)		risk→SZ → HSI → IBO → RTS(t = 2894)
Infected by Asia	Long	risk→DAX → DJI → SPX(t = 2573)	risk→DAX → IXI → DAX(t = 3063)		
	Long	risk→DAX → IXI → SPX(t = 2586)			
	Long	risk→SZ → HSI → DAX → SPX(t = 1499)		risk→SZ → HSI → DAX → SH(t = 3248)	risk→SZ → HSI → FTS → RTS(t = 1532)
Infected by Asia	Short	risk→SZ → HSI → FTS → SPX(t = 1504)	risk→SZ → HSI → CAC → DAX(t = 1472)	risk→SZ → HSI → FTS → SH(t = 3270)	risk→SZ → HSI → DAX → RTS(t = 1541)
	Short	risk→SZ → HSI → CAC → SPX(t = 1508)	risk→SZ → HSI → RTS → DAX(t = 1558)	risk→SZ → HSI → CAC → SH(t = 3326)	risk→SZ → HSI → CAC → RTS(t = 1544)
	Short	risk→SZ → HSI → RTS → SPX(t = 1644)		risk→SZ → HSI → RTS → SH(t = 3355)	
Infected by Asia	Medium	risk→SZ → HSI → DAX → SPX(t = 1499)			risk→SZ → HSI → FTS → RTS(t = 1532)
	Medium	risk→SZ → HSI → FTS → SPX(t = 1504)	risk→SZ → HSI → CAC → DAX(t = 1472)		risk→SZ → HSI → DAX → RTS(t = 1541)
	Medium	risk→SZ → HSI → CAC → SPX(t = 1508)	risk→SZ → HSI → RTS → DAX(t = 1558)		risk→SZ → HSI → CAC → RTS(t = 1544)
Infected by Asia	Long	risk→SZ → HSI → RTS → SPX(t = 1644)			
	Long	risk→DAX → CAC → SPX(t = 2582)	risk→DAX → CAC → DAX(t = 2546)		
	Long	risk→DAX → FTS → SPX(t = 2590)	risk→DAX → FTS → DAX(t = 2558)		
Infected by Asia	Short	risk→SZ → HSI → SPX(t = 1543)	risk→SZ → HSI → DAX(t = 1407)	risk→SZ → SH(t = 1181)	risk→SZ → HSI → RTS(t = 1424)
	Short	risk→SZ → HSI → SEN → SPX(t = 1601)	risk→SZ → HSI → N225 → DAX(t = 1499)	risk→SZ → HSI → SH(t = 1534)	risk→SZ → HSI → N225 → RTS(t = 1529)
	Short	risk→SZ → HSI → N225 → SPX(t = 1613)	risk→SZ → HSI → KS → DAX(t = 1526)	risk→SZ → HSI → SEN → SH(t = 1680)	risk→SZ → HSI → KS → RTS(t = 1536)
Infected by Asia	Medium	risk→SZ → HSI → KS → SPX(t = 1620)	risk→SZ → HSI → SEN → DAX(t = 1544)	risk→SZ → HSI → N225 → SH(t = 1682)	risk→SZ → HSI → SEN → RTS(t = 1543)
	Medium	risk→SZ → HSI → TW → SPX(t = 1755)	risk→SZ → HSI → TW → DAX(t = 1581)	risk→SZ → HSI → KS → SH(t = 1730)	risk→SZ → HSI → TW → RTS(t = 1596)
	Medium	risk→SZ → SPX(t = 1862)	risk→SZ → SH → DAX(t = 1728)	risk→SZ → HSI → TW → SH(t = 1763)	risk→SZ → RTS(t = 1612)
Infected by Asia	Long	risk→SZ → SH → SPX(t = 2427)			risk→SZ → SH → RTS(t = 1710)
	Long	risk→SZ → HSI → SPX(t = 1543)	risk→SZ → HSI → DAX(t = 1407)	risk→SZ → SH(t = 1181)	risk→SZ → HSI → RTS(t = 1424)
	Long	risk→SZ → HSI → SEN → SPX(t = 1601)	risk→SZ → HSI → N225 → DAX(t = 1499)	risk→SZ → HSI → SH(t = 1534)	risk→SZ → HSI → N225 → RTS(t = 1529)

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Table 10 (continued)

	SPX	DAX	SH	RTS
	risk→SZ → HSI → N225 → SPX(t = 1613)	risk→SZ → HSI → KS → DAX(t = 1526)		risk→SZ → HSI → KS → RTS(t = 1536)
	risk→SZ → HSI → KS → SPX(t = 1620)	risk→SZ → HSI → SEN → DAX(t = 1544)		risk→SZ → HSI → SEN → RTS(t = 1562)
	risk→SZ → HSI → TW → SPX(t = 1755)	risk→SZ → HSI → TW → DAX(t = 1581)		risk→SZ → HSI → TW → RTS(t = 1598)
	risk→SZ → SPX(t = 1862)	risk→SZ → SH → DAX(t = 1728)		risk→SZ → RTS(t = 1612)
	risk→SZ → SH → SPX(t = 2427)			risk→SZ → SH → RTS(t = 1710)
	Long		risk→SZ → SH(t = 1181)	
	Short	risk→SZ → AS→SPX(t = 1546)	risk→SZ → AS→DAX(t = 1470)	risk→SZ → AS→RTS(t = 1479)
Infected by Oceania	Medium	risk→SZ → AS→SPX(t = 1546)	risk→SZ → AS→SH(t = 1613)	risk→SZ → AS→RTS(t = 1479)
	Long			

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, and key node 3 (with the corresponding times in parentheses). "short," "media," and "long" represent the short-, medium-, and long- timescales. "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

different timescales is crucial due to the diverse investment strategies employed by investors. Some focus on short-term gains, while others prioritize long-term stability. In our analysis, we revisit the impact of four climate risks on the global stock market across short-term, medium-term, and long-term intervals. Given the varying resilience of markets to climate risks over different timescales, we utilize the BK approach to assess risk resilience across all markets. Through this analysis, we aim to examine the dynamic diffusion of these climate risks in the global stock market across various timescales. Figs. 8 to 11 depict the dynamic diffusion patterns of these climate risks, offering insights into how they influence global stock markets over different timeframes.

In Fig. 8, we focus on the impact of overall climate risk at varying timescales. On the left side, we observe the energy required for climate risk contagion at different stable edge numbers. It's notable that the wave source energy needed is highest in the long-term, followed by the medium-term, and lastly, the short-term risk. This suggests that stock markets exhibit varying degrees of resilience to risk across different timescales, with the system being most resilient in the long term, followed by the medium term, and the least in the short term.

On the right side of the figure, we illustrate changes in the number of connected edges in the network resulting from the diffusion of climate risk over time. Here, we set the wave source energy to 80,000 for all three timescales. Similar to findings in the top-left subplot of Fig. 3, initially, there are no edge formations during climate risk diffusion. It wasn't until around t equals 2000 that climate risk began to transmit in global stock markets, leading to an increase in the number of network edges.

Fig. 9 illustrates the findings regarding temperature risks. On the left side of the figure, we present the energy required to trigger the contagion of temperature risk across different timescales for varying numbers of stable network edges. Similar to Fig. 8, we observe that the wave source energy must be set highest for the long term, followed by the medium term, and finally, the short term, when considering the same number of stable network edges. This consistency in results suggests that the overall resilience of the system is highest in the long term, followed by the medium term, and finally the short term.

On the right side of the figure, we depict the dynamic changes in the number of network edges resulting from the impact of temperature risk on global stock markets over time, with the wave source energy set to 80,000 for all three timescales. Similar to the subplot in the top right of Fig. 3, we observe no formation of network edges during the initial stage of temperature risk contagion. It is only around $t = 2500$ that temperature risks begin to affect the global stock market, leading to an increase in the number of network edges. We also notice that the transmission of temperature risk occurs at a faster rate in the short term, followed by the medium term, with the slowest rate observed in the long term.

Furthermore, comparing Figs. 8 and 9, we observe that the contagion

of temperature risk in global stock markets tends to occur later than the contagion of overall climate risk across all three timescales.

Fig. 10 illustrates the findings regarding drought risk. On the left side of the figure, we plot the energy required to trigger the contagion of drought risk across different timescales for various numbers of stable network edges. Similar to Figs. 8 and 9, we observe that the long-term wave source energy necessitates the highest setting, followed by the medium-term and finally the short-term when reaching the same number of stable network edges. This consistency in results reinforces the notion that the overall resilience of the system is highest in the long term, followed by the medium term, and finally the short term.

On the right side of the figure, we present the dynamic changes over time in the number of connected edges in the network influenced by drought risk on global stock markets, with the wave source energy set to 80,000 for all three timescales. Similar to the outcomes in the lower-right subplot of Fig. 3, no connected edge count is established during the initial stage of risk diffusion. It is only around $t = 1500$ that the drought risk reaches the global stock markets, exhibiting the fastest transmission in the short term and the slowest in the long term.

It is noteworthy that the formation of network-connected edges under drought risk occurs earlier compared to overall climate risk and temperature risk, indicating that drought risk has a relatively quicker impact on the global stock markets.

Fig. 11 illustrates the outcomes regarding precipitation risk. On the left side of the figure, we present the energy required to trigger the contagion of precipitation risk across different timescales for various numbers of stable network edges. Consistent with previous findings, we observe that higher wave source energies are required as the number of stable edges increases, with the highest energy needed for the long term and the lowest for the short term. This pattern underscores the greater resilience or risk absorption capacity of global stock markets in the long run compared to shorter timescales.

On the right side of the figure, we display the dynamic changes over time in the number of connected edges in the network influenced by precipitation risk on global stock markets. Here, the wave source energies for the short-term, medium-term, and long-term are all set to 80,000. Similar to the structure of the lower-right subplot in Fig. 3, no edge formation occurs in the early stages of risk diffusion. It is only around $t = 2500$ that the precipitation risk reaches the global equity markets, once again demonstrating the fastest transmission in the short term and the slowest in the long term.

This observation could be attributed to the fact that during the initial stages of risk diffusion, the risk has a greater distance to cover before reaching the stock markets, thus requiring more time. However, once the stock markets are infected with the risk, it rapidly spreads within the system, leading to a swift increase in the number of stable contiguous edges. It is noteworthy that the formation of network edges under

Table 11

Comparison of the path and time of short-, medium-, and long-timescales: precipitation risk.

		SPX	DAX	SH	RTS
Total number of paths	Short	16	14	12	15
	Medium	16	14	3	12
	Long	5	3	2	0
Total number of nodes	Short	15	15	11	15
	Medium	15	15	2	12
	Long	4	2	1	0
Key node 1 (times)	Short	SZ(15)	SZ(13)	SZ(12)	SZ(15)
	Medium	SZ(15)	SZ(13)	SZ(2)	SZ(12)
	Long	IXI(4)	IXI(2)		
Key node 2 (times)	Short	HSI(12)	HSI(11)	HSI(9)	HSI(12)
	Medium	HSI(12)	HSI(11)		HSI(10)
	Long				
Key node 3 (times)	Short	DAX(3)	DAX(3)		DAX(4)
	Medium	DAX(3)	DAX(3)		DAX(4)
	Long				
The first contagion	Short	risk→SZ → HSI → DAX → SPX(t = 1615)	risk→SZ → HSI → DAX(t = 1523)	risk→SZ → SH(t = 1297)	risk→SZ → HSI → RTS(t = 1540)
	Medium	risk→SZ → HSI → DAX → SPX(t = 1615)	risk→SZ → HSI → DAX(t = 1523)	risk→SZ → SH(t = 1297)	risk→SZ → HSI → RTS(t = 1540)
	Long	risk→IXI → SPX(t = 2561)	risk→IXI → DAX(t = 2606)	risk→SZ → SH(t = 1297)	
Infected by precipitation risk	Short	risk→SPX(t = 2831)	risk→DAX(t = 2734)	risk→SH(t = 1680)	
	Medium	risk→SPX(t = 2831)	risk→DAX(t = 2734)	risk→SH(t = 1680)	
	Long	risk→SPX(t = 2831)	risk→DAX(t = 2734)	risk→SH(t = 1680)	
Infected by America	Short	risk→SZ → HSI → DAX → DJI → SPX(t = 1668)	risk→SZ → HSI → DAX → DJI → DAX(t = 1710)		risk→SZ → HSI → DAX → IXI → RTS(t = 1905)
	Medium	risk→SZ → HSI → DAX → IXI → SPX(t = 1681)	risk→SZ → HSI → DAX → IXI → DAX(t = 1726)		risk→SZ → HSI → DAX → SPX → RTS(t = 2749)
	Long	risk→SZ → HSI → IBO → SPX(t = 1828)	risk→SZ → HSI → IBO → DAX(t = 1876)		risk→SZ → HSI → DAX → DJI → RTS(t = 2787)
Infected by Europe	Short	risk→SZ → HSI → DAX → DJI → SPX(t = 1668)	risk→SZ → HSI → DAX → DJI → DAX(t = 1710)		risk→SZ → HSI → DAX → IXI → RTS(t = 2749)
	Medium	risk→SZ → HSI → DAX → IXI → SPX(t = 1681)	risk→SZ → HSI → DAX → IXI → DAX(t = 1726)		risk→SZ → HSI → DAX → SPX → RTS(t = 2782)
	Long	risk→SZ → HSI → IBO → SPX(t = 1828)	risk→SZ → HSI → IBO → DAX(t = 1876)		risk→SZ → HSI → DAX → DJI → RTS(t = 2787)
Infected by Asia	Short	risk→IXI → SPX(t = 2561)	risk→IXI → DAX(t = 2606)		risk→SZ → HSI → IBO → RTS(t = 2933)
	Medium	risk→IXI → DJI → SPX(t = 2619)			
	Long	risk→SZ → HSI → DAX → SPX(t = 1615)			
Infected by Asia	Short	risk→SZ → HSI → FTS → SPX(t = 1620)	risk→SZ → HSI → CAC → DAX(t = 1588)	risk→SZ → HSI → FTS → SH (t = 3396)	risk→SZ → HSI → FTS → RTS(t = 1648)
	Medium	risk→SZ → HSI → CAC → SPX(t = 1624)	risk→SZ → HSI → RTS → DAX(t = 1674)	risk→SZ → HSI → DAX → SH (t = 3426)	risk→SZ → HSI → DAX → RTS(t = 1657)
	Long	risk→SZ → HSI → RTS → SPX(t = 1760)		risk→SZ → HSI → CAC → SH (t = 3452)	risk→SZ → HSI → CAC → RTS(t = 1660)
Infected by Asia	Short	risk→SZ → HSI → DAX → SPX(t = 1615)		risk→SZ → HSI → RTS → SH (t = 3661)	
	Medium	risk→SZ → HSI → FTS → SPX(t = 1620)	risk→SZ → HSI → CAC → DAX(t = 1588)		risk→SZ → HSI → DAX → RTS(t = 1657)
	Long	risk→SZ → HSI → CAC → SPX(t = 1624)	risk→SZ → HSI → RTS → DAX(t = 1674)		risk→SZ → HSI → CAC → RTS(t = 1660)
Infected by Asia	Short	risk→SZ → HSI → RTS → SPX(t = 1760)			
	Medium	risk→IXI → DAX → SPX(t = 2826)	risk→IXI → CAC → DAX(t = 2852)		
	Long	risk→IXI → CAC → SPX(t = 2888)			
Infected by Asia	Short	risk→SZ → HSI → SPX(t = 1659)	risk→SZ → HSI → DAX(t = 1523)	risk→SZ → SH(t = 1297)	risk→SZ → HSI → RTS(t = 1540)
	Medium	risk→SZ → HSI → SEN → SPX(t = 1717)	risk→SZ → HSI → N225 → DAX(t = 1615)	risk→SZ → HSI → SH(t = 1650)	risk→SZ → HSI → N225 → RTS(t = 1645)
	Long	risk→SZ → HSI → N225 → SPX(t = 1729)	risk→SZ → HSI → KS → DAX(t = 1642)	risk→SZ → HSI → SEN → SH (t = 1796)	risk→SZ → HSI → KS → RTS(t = 1652)
Infected by Asia	Short	risk→SZ → HSI → KS → SPX(t = 1736)	risk→SZ → HSI → SEN → DAX(t = 1660)	risk→SZ → HSI → N225 → SH(t = 1798)	risk→SZ → HSI → SEN → RTS(t = 1659)
	Medium	risk→SZ → HSI → TW → SPX(t = 1871)	risk→SZ → HSI → TW → DAX(t = 1697)	risk→SZ → HSI → KS → SH(t = 1876)	risk→SZ → HSI → TW → RTS(t = 1714)
	Long	risk→SZ → SPX(t = 1978)	risk→SZ → SH → DAX(t = 1844)	risk→SZ → HSI → TW → SH (t = 1879)	risk→SZ → RTS(t = 1728)
Infected by Asia	Short	risk→SZ → SH → SPX(t = 2543)			risk→SZ → SH → RTS(t = 1826)
	Medium	risk→SZ → HSI → SPX(t = 1659)	risk→SZ → HSI → DAX(t = 1523)	risk→SZ → SH(t = 1297)	risk→SZ → HSI → RTS(t = 1540)
	Long	risk→SZ → HSI → SEN → SPX(t = 1717)	risk→SZ → HSI → N225 → DAX(t = 1615)	risk→SZ → HSI → SH(t = 1650)	risk→SZ → HSI → N225 → RTS(t = 1649)

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Table 11 (continued)

	SPX	DAX	SH	RTS
	risk→SZ → HSI → N225 → SPX(= 1729)	risk→SZ → HSI → KS → DAX(= 1642)		risk→SZ → HSI → KS → RTS(= 16,782)
	risk→SZ → HSI → KS → SPX(= 1736)	risk→SZ → HSI → SEN → DAX(= 1660)		risk→SZ → RTS(= 1728)
	risk→SZ → HSI → TW → SPX(= 1871)	risk→SZ → HSI → TW → DAX(= 1697)		risk→SZ → SH → RTS(= 1826)
	risk→SZ → SPX(= 1978)	risk→SZ → SH → DAX(= 1844)		
	risk→SZ → SH → SPX(= 2543)			
Long			risk→SZ → SH(= 1297)	
Short	risk→SZ → AS→SPX(= 1662)	risk→SZ → AS→DAX(= 1586)	risk→SZ → AS→SH(= 1729)	risk→SZ → AS→RTS(= 1595)
Medium	risk→SZ → AS→SPX(= 1662)	risk→SZ → AS→DAX(= 1586)		
Long				

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, and key node 3 (with the corresponding times in parentheses). "short," "media," and "long" represent the short-, medium-, and long- timescales. "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

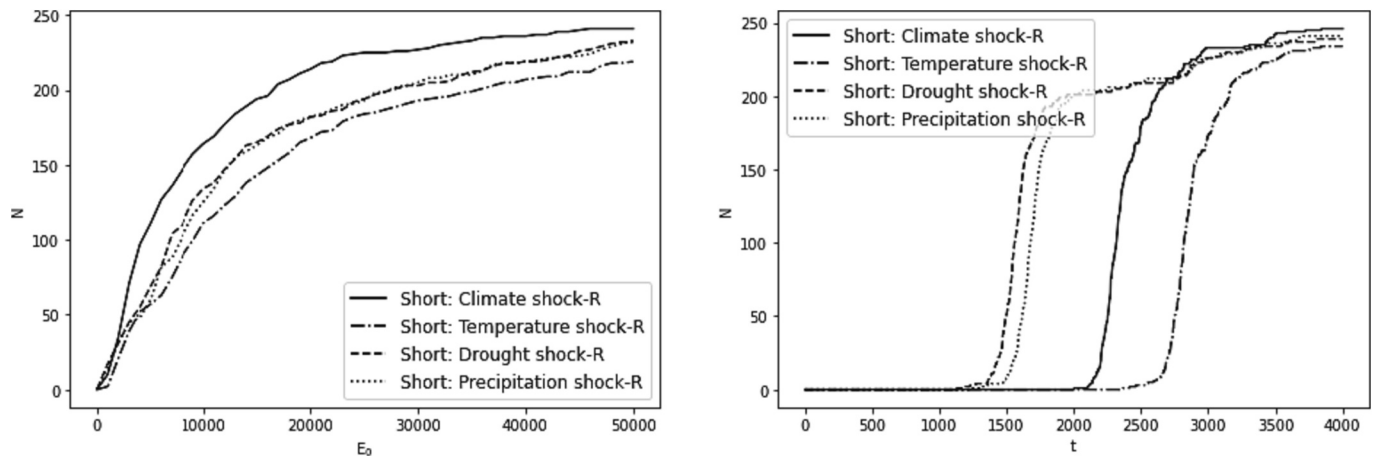


Fig. 12. Comparison of the dynamic ripple diffusion process of four climate risks-R: short-timescale.

Notes: This figure compares the dynamic ripple diffusion process of overall climate risk, temperature risk, drought risk, and precipitation risk to stock markets' returns in the short timescale. E_0 represent the initial wave source energy value, while N denotes the total edges of the stable network. t represent the time for each climate risk to be transmitted.

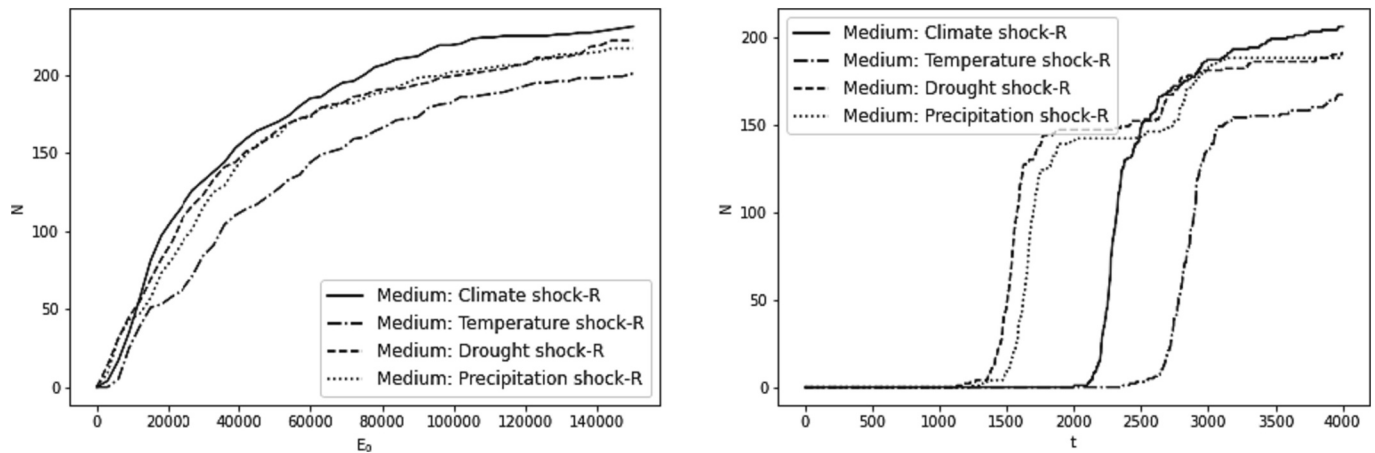


Fig. 13. Comparison of the dynamic ripple diffusion process of four climate risks-R: medium-timescale.

Notes: This figure compares the dynamic ripple diffusion process of overall climate risk, temperature risk, drought risk, and precipitation risk to stock markets' returns in the medium timescale. E_0 represent the initial wave source energy value, while N denotes the total edges of the stable network. t represent the time for each climate risk to be transmitted.

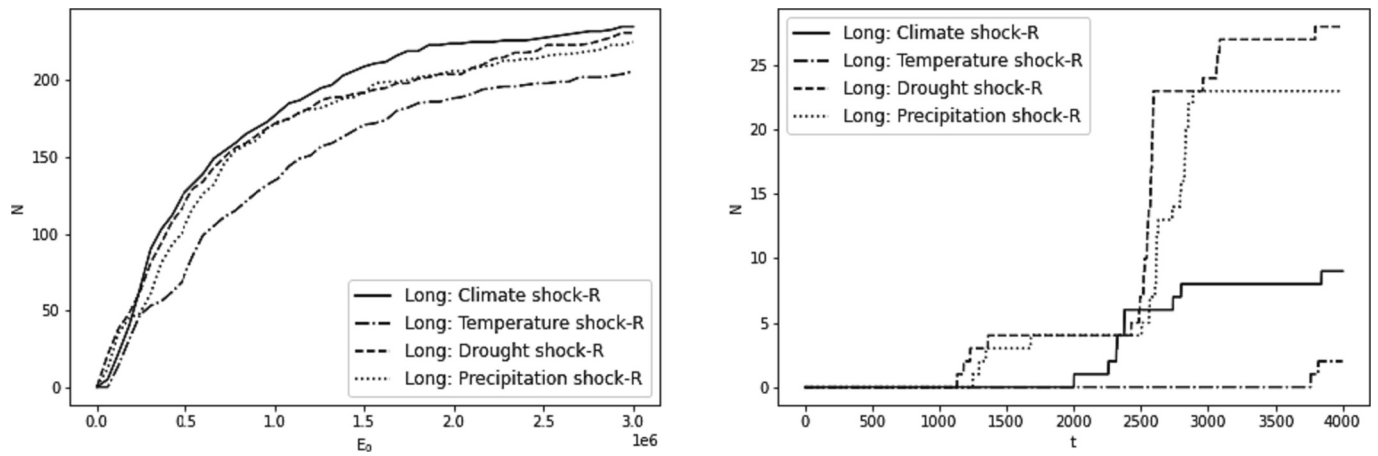


Fig. 14. Comparison of the dynamic ripple diffusion process of four climate risks-R: long-timescale.

Notes: This figure compares the dynamic ripple diffusion process of overall climate risk, temperature risk, drought risk, and precipitation risk to stock markets' returns in the long timescale. E_0 represent the initial wave source energy value, while N denotes the total edges of the stable network. t represent the time for each climate risk to be transmitted.

precipitation risk begins at a similar time as temperature risk, but earlier than overall climate risk and drought risk, indicating the relatively quicker impact of precipitation risk on the global stock markets.

In summary, regardless of the type of climate risk, the long-term time scale demands the highest initial wave source energy, whereas the short-term time scale requires the lowest initial wave source energy to achieve the same number of stable network edges. Moreover, when considering the same initial wave source energy, short-term climate risks demonstrate the quickest propagation and lead to the highest number of stable network edges, whereas long-term risks spread at a slower rate and result in a smaller number of edges. These findings indicate that the overall system exhibits greater resilience to risk over the long term. Consequently, short-term investors should allocate more attention to the implications of climate risk compared to long-term investors.

4.4.2. Typical pathways and timing at different timescales

Upon examining the dynamic diffusion process of the four climate risks on global stock markets across diverse timescales, we summarize the pathways and timing of risk transmission to representative financial markets. The results are encapsulated in Tables 8 to 11.

Table 8 encapsulates the pathways and timing of overall climate risk transmission to representative financial markets across different timescales. In the short term, 15 transmission paths to the SPX market are evident, dwindling to 14 in the medium term and none in the long term. Specifically, among the 14 transmission paths to the SPX market in the short term, three stem from the Americas, four from Europe, seven from Asia, and one from Oceania. An early path observed is the transmission to the SPX market through the DAX market in Europe. In the medium term, there is a decrease in paths from Asia to the SPX market via the SH market, with a delay in the occurrence of the path to the SPX market via the SZ market compared to the short term.

Regarding the DAX market, 14 transmission paths are identified in both the short and medium term, with origins from the Americas, Europe, Asia, and Oceania. The earliest path to the DAX market is via the Asian HSI market. While the transmission paths from continents remain consistent in both the short and medium term, there is a delay in the transmission path from the Asian SH and SZ markets in the medium term compared to the short term. Long-term results are more diverse, with only two paths reaching the DAX market, one directly from the wave source and one from the European CAC market, with the earliest path from the wave source occurring at $t = 2259$ moments. The timing of the first risk to the long-term DAX market is also delayed compared to the short and medium terms.

In the short term, there are 12 paths of risk transmission to the SH

market, originating from various regions such as the wave source, Europe, Asia, and Oceania. However, in the medium term, the number of paths decreases to four, including one from the wave source and three from Asia. Notably, the paths from Europe and Oceania are absent in the medium term. Furthermore, the earliest occurrence of risk contagion in both the short and medium term is at $t = 2260$ moments, originating from the SZ market. However, in the long term, no transmission to the SH market is observed.

Similarly, in the short term, 14 transmission paths are identified for the RTS market, with origins from the Americas, Europe, Asia, and Oceania. The earliest observed path of transmission originates from the Asian HSI market. In the medium term, there is a reduction in the number of paths compared to the short term, with one path from the Asian SH market being eliminated. Additionally, the timing of the three European paths and the path from Asia's mainland markets is delayed compared to the short term. However, the earliest path still originates from the Asian HSI market. Notably, no transmission paths to the RTS market are observed in the long term.

Table 9 summarizes the paths and moments of temperature risk transmission to representative financial markets at different timescales. It is observed that throughout the risk contagion process, there are 15 paths of transmission to the SPX market in the short term, decreasing to 14 paths in the medium term, and only one path in the long term. Specifically, out of the 15 paths of transmission to the SPX market in the short term, three come from the Americas, four from Europe, seven from Asia, and one from Oceania. In both the short and medium term, the first transmission occurs through the DAX market in Europe, happening at $t = 2771$ moments. However, in the long term, the earliest transmission to the SPX market occurs via the IXI market in the Americas, happening at $t = 3820$ moments.

Table 10 summarizes the paths and moments of drought risk transmission to representative financial markets at different timescales. In both the short term and medium term, there are 16 paths of transmission to the SPX market, while in the long term, it decreases to six paths. In both the short term and medium term, the initial transmission to the SPX market occurs through the DAX market, while in the long term, it occurs at a delayed moment.

Table 11 summarizes the paths and timings of precipitation risk transmission to representative financial markets at different timescales. It is observed that there are 16 paths transmitting to the SPX market in the short term and medium term, which is reduced to five paths in the long term. Moreover, the first paths to transmit to the SPX market in the short term and medium term occur through the DAX market, while in the long term, the transmission occurs through the IXI market.

Table 12

Comparison of the path and time of four types of climate risks.

		SPX	DAX	SH	RTS
Total number of paths	Climate risk	15	14	11	13
	Temperature risk	15	12	5	15
	Drought risk	16	14	7	14
	Precipitation risk	16	14	5	15
Total number of nodes	Climate risk	15	15	10	13
	Temperature risk	15	13	5	16
	Drought risk	15	15	6	14
	Precipitation risk	15	15	4	15
Key node 1 (times)	Climate risk	HSI(15)	HSI(14)	HSI(10)	HSI(13)
	Temperature risk	SH(13)	SH(10)	SH(4)	SH(13)
	Drought risk	SZ(15)	SZ(13)	SZ(6)	SZ(14)
	Precipitation risk	SZ(15)	SZ(13)	SZ(4)	SZ(15)
Key node 2 (times)	Climate risk	DAX(3)	DAX(3)		DAX(3)
	Temperature risk	HSI(8)	HSI(6)		HSI(10)
	Drought risk	HSI(12)	HSI(11)	HSI(5)	HSI(11)
	Precipitation risk	HSI(12)	HSI(11)	HSI(3)	HSI(12)
Key node 3 (times)	Climate risk	SZ(2)	SZ(2)		
	Temperature risk	DAX(3)	DAX(2)		DAX(4)
	Drought risk	DAX(3)	DAX(3)		DAX(3)
	Precipitation risk	DAX(3)	DAX(3)		DAX(4)
Key node 4 (times)	Climate risk				
	Temperature risk	RTS(2)	RTS(2)		
	Drought risk				
	Precipitation risk				
The first contagion	Climate risk	risk→HSI→DAX→SPX(t = 2231)	risk→HSI→DAX(t = 2139)	risk→HSI→SZ→SH(t = 2260)	risk→HSI→RTS(t = 2156)
	Temperature risk	risk→SH→HSI→DAX→SPX(t = 2771)	risk→SH→HSI→DAX(t = 2679)	risk→SH(t = 2368)	risk→RTS(t = 2596)
	Drought risk	risk→SZ→HSI→DAX→SPX(t = 1499)	risk→SZ→HSI→DAX(t = 1407)	risk→SZ→SH(t = 1181)	risk→SZ→HSI→RTS(t = 1424)
	Precipitation risk	risk→SZ→HSI→DAX→SPX(t = 1615)	risk→SZ→HSI→DAX(t = 1523)	risk→SZ→SH(t = 1297)	risk→SZ→HSI→RTS(t = 1540)
Infected by risk	Climate risk			risk→SH(t = 2621)	
	Temperature risk			risk→SH(t = 2368)	risk→RTS(t = 2596)
	Drought risk	risk→SPX(t = 3797)	risk→DAX(t = 2428)	risk→SH(t = 1363)	
	Precipitation risk	risk→SPX(t = 2831)	risk→DAX(t = 2734)	risk→SH(t = 1680)	
Infected by America	Climate risk	risk→HSI→DAX→DJI→SPX(t = 2284)	risk→HSI→DAX→SPX→DAX(t = 2324)		risk→HSI→DAX→SPX→RTS(t = 2452)
		risk→HSI→DAX→IXI→SPX(t = 2297)	risk→HSI→DAX→DJI→DAX(t = 2326)		risk→HSI→DAX→IXI→RTS(t = 2485)
		risk→HSI→IBO→SPX(t = 2444)	risk→HSI→DAX→IXI→DAX(t = 2342)		risk→HSI→IBO→RTS(t = 2595)
			risk→HSI→IBO→DAX(t = 2492)		
Infected by America	Temperature risk	risk→SH→HSI→DAX→DJI→SPX(t = 2824)	risk→SH→HSI→DAX→SPX→DAX(t = 2864)		risk→SH→HSI→DAX→DJI→RTS(t = 3035)
		risk→SH→HSI→DAX→IXI→SPX(t = 2837)	risk→SH→HSI→DAX→IXI→DAX(t = 2882)		risk→SH→HSI→DAX→SPX→RTS(t = 3037)
		risk→RTS→IBO→SPX(t = 3014)	risk→RTS→IBO→DAX(t = 3062)		risk→SH→HSI→DAX→IXI→RTS(t = 3077)
					risk→RTS→IBO→RTS(t = 3165)
Drought risk		risk→SZ→HSI→DAX→DJI→SPX(t = 1552)	risk→SZ→HSI→DAX→SPX→DAX(t = 1592)		risk→SZ→HSI→IBO→RTS(t = 1863)
		risk→SZ→HSI→DAX→IXI→SPX(t = 1565)	risk→SZ→HSI→DAX→DJI→DAX(t = 1594)		risk→SZ→HSI→DAX→SPX→RTS(t = 2741)
		risk→SZ→HSI→IBO→SPX(t = 1712)	risk→SZ→HSI→DAX→IXI→DAX(t = 1610)		risk→SZ→HSI→DAX→IXI→RTS(t = 2774)
			risk→SZ→HSI→IBO→DAX(t = 1760)		

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Table 12 (continued)

	SPX	DAX	SH	RTS	
Infected by Europe	Precipitation risk	risk→SZ → HSI → DAX → DJI → SPX(t = 1668)	risk→SZ → HSI → DAX → SPX → DAX(t = 1708)	risk→SZ → HSI → IBO → RTS(t = 2173)	
		risk→SZ → HSI → DAX → IXI → SPX(t = 1681)	risk→SZ → HSI → DAX → DJI → DAX(t = 1710)	risk→SZ → HSI → DAX → IXI → RTS(t = 2749)	
		risk→SZ → HSI → IBO → SPX(t = 1828)	risk→SZ → HSI → DAX → IXI → DAX(t = 1726)	risk→SZ → HSI → DAX → SPX → RTS(t = 2782)	
			risk→SZ → HSI → IBO → DAX(t = 1876)	risk→SZ → HSI → DAX → DJI → RTS(t = 2787)	
	Climate risk	risk→HSI → DAX → SPX(t = 2231)		risk→HSI → DAX → SH(t = 3079)	risk→HSI → FTS → RTS(t = 2264)
		risk→HSI → FTS → SPX(t = 2236)	risk→HSI → CAC → DAX(t = 2204)	risk→HSI → CAC → SH(t = 3157)	risk→HSI → DAX → RTS(t = 2273)
		risk→HSI → CAC → SPX(t = 2240)	risk→HSI → RTS → DAX(t = 2290)	risk→HSI → FTS → SH(t = 3517)	risk→HSI → CAC → RTS(t = 2276)
		risk→HSI → RTS → SPX(t = 2376)			
	Temperature risk	risk→SH → HSI → DAX → SPX(t = 2771)			risk→SH → HSI → FTS → RTS(t = 2847)
		risk→SH → HSI → FTS → SPX(t = 2776)	risk→RTS → DAX(t = 2730)	risk→RTS → SH(t = 3389)	risk→SH → HSI → CAC → RTS(t = 2859)
		risk→SH → HSI → CAC → SPX(t = 2780)	risk→SH → HSI → CAC → DAX(t = 2744)		risk→SH → HSI → DAX → RTS(t = 2865)
		risk→RTS → SPX(t = 2816)			
Drought risk	risk→SZ → HSI → DAX → SPX(t = 1499)		risk→SZ → HSI → DAX → SH (t = 3248)	risk→SZ → HSI → FTS → RTS(t = 1532)	
	risk→SZ → HSI → FTS → SPX(t = 1504)	risk→SZ → HSI → CAC → DAX(t = 1472)	risk→SZ → HSI → FTS → SH (t = 3270)	risk→SZ → HSI → DAX → RTS(t = 1541)	
	risk→SZ → HSI → CAC → SPX(t = 1508)	risk→SZ → HSI → RTS → DAX(t = 1558)	risk→SZ → HSI → CAC → SH (t = 3326)	risk→SZ → HSI → CAC → RTS(t = 1544)	
	risk→SZ → HSI → RTS → SPX(t = 1644)				
Precipitation risk	risk→SZ → HSI → DAX → SPX(t = 1615)			risk→SZ → HSI → FTS → RTS(t = 1648)	
	risk→SZ → HSI → FTS → SPX(t = 1620)	risk→SZ → HSI → CAC → DAX(t = 1588)	risk→SZ → HSI → DAX → SH (t = 3554)	risk→SZ → HSI → DAX → RTS(t = 1657)	
	risk→SZ → HSI → CAC → SPX(t = 1624)	risk→SZ → HSI → RTS → DAX(t = 1674)	risk→SZ → HSI → CAC → SH (t = 3632)	risk→SZ → HSI → CAC → RTS(t = 1660)	
	risk→SZ → HSI → RTS → SPX(t = 1760)				
Infected by Asia	Climate risk	risk→HSI → SPX(t = 2275)	risk→HSI → DAX(t = 2139)	risk→HSI → SZ → SH(t = 2260)	risk→HSI → RTS(t = 2156)
		risk→HSI → SEN → SPX(t = 2333)	risk→HSI → N225 → DAX(t = 2231)	risk→HSI → SH(t = 2266)	risk→HSI → N225 → RTS(t = 2261)
		risk→HSI → N225 → SPX(t = 2345)	risk→HSI → KS → DAX(t = 2258)	risk→HSI → N225 → SH(t = 2414)	risk→HSI → KS → RTS(t = 2268)
		risk→HSI → KS → SPX(t = 2352)	risk→HSI → SEN → DAX(t = 2276)	risk→HSI → KS → SH (t = 2492)	risk→HSI → SEN → RTS(t = 2275)
	Temperature risk	risk→HSI → TW → SPX(t = 2487)	risk→HSI → TW → DAX(t = 2313)	risk→HSI → TW → SH (t = 2495)	risk→HSI → TW → RTS(t = 2328)
		risk→HSI → SZ → SPX(t = 2941)	risk→HSI → SZ → DAX(t = 2661)	risk→HSI → SEN → SH(t = 2902)	
		risk→HSI → SZ → SH → SPX(t = 3866)	risk→HSI → SZ → SH → DAX(t = 2807)		
		risk→SH → HSI → SPX(t = 2815)			
	Drought risk	risk→SH → SEN → SPX(t = 2854)	risk→SH → HSI → DAX(t = 2679)		risk→SH → HSI → RTS(t = 2696)
		risk→SH → HSI → N225 → SPX (t = 2885)	risk→SH → HSI → N225 → DAX (t = 2771)	risk→SH → SZ → SH(t = 2464)	risk→SH → SZ → RTS(t = 2895)
		risk→SH → HSI → KS → SPX(t = 2892)	risk→SH → SEN → DAX(t = 2797)	risk→SH → HSI → SH(t = 2806)	risk→SH → SEN → RTS(t = 2913)
		risk→SH → HSI → TW → SPX(t = 3040)	risk→SH → HSI → TW → DAX(t = 2853)	risk→SH → SEN → SH(t = 3998)	risk→SH → HSI → KS → RTS(t = 2962)
Precipitation risk	risk→SH → SZ → SPX(t = 3145)	risk→SH → SZ → DAX(t = 2865)		risk→SH → HSI → N225 → RTS(t = 2970)	
	risk→SH → SPX(t = 3613)	risk→SH → DAX(t = 2914)		risk→SH → HSI → TW → RTS(t = 3048)	
	risk→SZ → HSI → SPX(t = 1543)				
	risk→SZ → HSI → SEN → SPX(t = 1601)	risk→SZ → HSI → DAX(t = 1407)		risk→SZ → HSI → RTS(t = 1424)	

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Table 12 (continued)

		SPX	DAX	SH	RTS
		= 1729)	1642)		1652)
		risk→SZ → HSI → KS → SPX(t = 1736)	risk→SZ → HSI → SEN → DAX(t = 1660)		risk→SZ → HSI → SEN → RTS(t = 1659)
		risk→SZ → HSI → TW → SPX(t = 1871)	risk→SZ → HSI → TW → DAX(t = 1697)		risk→SZ → HSI → TW → RTS(t = 1714)
		risk→SZ → SPX(t = 1978)	risk→SZ → SH → DAX(t = 1844)		risk→SZ → RTS(t = 1728)
		risk→SZ → SH → SPX(t = 2543)			risk→SZ → SH → RTS(t = 1826)
	Climate risk	risk→HSI → AS→SPX(t = 2285)	risk→HSI → AS→DAX(t = 2209)	risk→HSI → AS→SH(t = 2352)	risk→HSI → AS→RTS(t = 2218)
	Temperature risk	risk→SH → AS→SPX(t = 2801)	risk→SH → AS→DAX(t = 2725)		risk→SH → AS→RTS(t = 2887)
	Drought risk	risk→SZ → AS→SPX(t = 1546)	risk→SZ → AS→DAX(t = 1470)		risk→SZ → AS→RTS(t = 1479)
	Precipitation risk	risk→SZ → AS→SPX(t = 1662)	risk→SZ → AS→DAX(t = 1586)		risk→SZ → AS→RTS(t = 1595)

Notes: "Total number of paths" represents the total count of paths through which risk is transmitted to the stock markets. "Key node" refers to the nodes that appear more frequently in all the paths through which risk propagates from the source to the stock markets, excluding the initial and final nodes. The key nodes are sorted based on their occurrence frequency, and they are denoted as key node 1, key node 2, key node 3, and key node 4 (with the corresponding times in parentheses). "short," "media," and "long" represent the short-, medium-, and long- timescales. "Infected by the Americas," "Infected by Europe," "Infected by Asia," and "Infected by Oceania" represent the nodes through which the shocks are transmitted to the stock markets (with the corresponding times in parentheses).

In conclusion, the findings underscore a dynamic pattern in the transmission of climate risks to financial markets, with a decrease in complexity over longer time horizons. Short-term investors need to closely monitor climate risks, given their intricate interplay with market dynamics, while long-term investors should consider strategies aimed at building resilience over time. Proactive risk management strategies tailored to different timeframes are essential for safeguarding financial markets against the impacts of climate change and enhancing overall market resilience.

4.5. Comparison of four types climate risks

4.5.1. Diffusion processes across four types of climate risks

To deepen our understanding of the influence of climate risks on global equity markets, we compare the diffusion processes and pathways of the four climate risks. Fig. 2 illustrates the change in the number of stable network edges with wave source energy. It's evident that for each climate risk, the number of stable network edges gradually increases with rising wave source energy, albeit at a diminishing rate. Comparing the four climate risks, at lower wave source energy levels, drought risk exhibits the widest spread, followed by precipitation risk, climate risk, and lastly temperature risk. However, with a slight increase in wave source energy, climate risk demonstrates the broadest reach, while drought and precipitation risks are relatively equal, and temperature risk has the least impact.

In Fig. 3, we depict the number of network edges formed by the four climate risks in the global stock market over time at the maximum wave source energy. Initially, none of the four climate risks form network edges as it takes time for them to propagate and reach the stock market due to considerable distances. Notably, drought risk is the first to start spreading, followed by precipitation risk, climate risk, and finally temperature risk. This sequence may be attributed to the more immediate effects of drought and precipitation risks on people's lives, while the impact of temperature risks takes longer to manifest.

Fig. 12 illustrates the diffusion results of the four climate risks in the financial market during the short term. The climate risk exhibits the widest spread at the same wave source energy level, with impacts of drought, and precipitation risks relatively comparable and temperature risk having the smallest influence. In the temporal evolution of network edges, drought and temperature risks are the first to propagate, followed by climate risk and then precipitation risk.

In Fig. 13, we examine the diffusion results of the four climate risks in the financial market during the medium term. On the left side, we observe the change in the number of stable network edges with wave source energy. This pattern resembles Fig. 2, where lower wave source energy levels result in drought risk exhibiting the widest spread,

followed by precipitation risk, overall climate risk, and finally temperature risk. However, with a slight increase in wave source energy, we notice that overall climate risk spreads most extensively. This could be attributed to its comprehensive coverage of various dimensions of climate risks, leading to a more significant impact on financial markets and resulting in a higher number of network edges. Drought risk and precipitation risk exhibit relatively comparable impacts, while temperature risk has the smallest influence.

On the right side, we present the temporal evolution of network edges formed by the four climate risks in the medium term, at the maximum wave source energy. Similarly to previous findings, in the initial stage of diffusion, none of the four climate risks form network edges. Subsequently, drought risk is the first to spread in the global financial market, followed by precipitation risk, overall climate risk, and finally temperature risk.

In Fig. 14, we examine the diffusion results of the four climate risks in the financial market over the long-term time scale. On the left side, we observe a change in the number of stable network edges with wave source energy, which aligns with previous findings. Climate risk exhibits the widest spread, followed by drought risk and precipitation risk, while temperature risk has the lowest impact range.

On the right side, we depict the temporal evolution of network edges formed by the four climate risks in the long term, at the maximum wave source energy. Similarly to earlier observations, none of the four climate risks form network edges in the initial stage of diffusion. Subsequently, drought risk is the first to spread in the global financial market, followed by precipitation risk, climate risk, and finally temperature risk.

In summary, across all time scales—short-term, medium-term, and long-term—the overall climate risk consistently demonstrates the widest impact range among the four climate risks. Following closely behind are drought risk and precipitation risk, which exhibit comparable levels of impact, while temperature risk shows the lowest impact range. Additionally, in the transmission process, drought risk is the first to propagate, succeeded by precipitation risk, climate risk, and finally temperature risk. These findings underscore the importance for investors to closely monitor drought and precipitation events, given their rapid propagation compared to other climate risks.

4.5.2. Typical pathways and timing across four types of climate risks

In the preceding analysis, we examined the dynamic processes of the four climate risks on global stock markets. Here, we consolidate the pathways and timing of these risks transmitting to representative financial markets, as delineated in Table 12. Notably, the number of pathways through which climate risk and temperature risk transmit to the SPX market is identical at 15 pathways each. Similarly, both drought risk and precipitation risk have 16 pathways to the SPX market.

However, disparities emerge in their pivotal nodes.

Within the overall climate risk, the HSI market appears fifteen times, DAX three times, and SZ twice. Contrastingly, within the 15 pathways of temperature risk, SH emerges thirteen times, HSI eight times, DAX three times, and RTS twice. For both drought risk and precipitation risk, SZ appears fifteen times, HSI twelve times, and DAX three times. Additionally, RTS serves as a key node for temperature risk. This underscores the necessity for distinct financial market monitoring concerning different types of climate risks within the SPX market. Notably, the initial pathways for all four risks to the SPX market traverse through the DAX market, albeit with varied timing occurrences. The sequence follows the transmission order: drought risk, precipitation risk, overall climate risk, and finally temperature risk, aligning with the earlier analysis in Section 4.5.1.

Similarly, the number of pathways through which climate risks, drought risks, and precipitation risks transmit to the DAX market equates to 14 pathways each, while temperature risk has 12 pathways. In climate risk pathways, HSI appears 14 times, DAX three times, and SZ twice. Temperature risk pathways feature SH ten times, HSI six times, DAX twice, and RTS twice. For both drought risk and precipitation risk pathways, SZ appears 13 times, HSI 11 times, and DAX three times. Notably, the transmission to the DAX market commences through the HSI market for all four risks, following the transmission order: drought risk, precipitation risk, climate risk, and temperature risk.

Regarding the SH market, climate risk exhibits 11 pathways, while temperature and precipitation risks both have 5, and drought risk has 7 pathways. Noteworthy nodes include HSI appearing ten times in climate risk pathways, SH four times in temperature risk pathways, SZ six times, and HSI five times in drought risk pathways, and SZ four times and HSI three times in precipitation risk pathways. The sequence of transmission to the SH market aligns with the transmission order observed in the SPX and DAX markets, except for temperature risk, which is initially transmitted directly through the wave source and occurs later compared to the other risks.

In the case of the RTS market, climate risk presents 13 pathways, while temperature and precipitation risks both have 15, and drought risk has 14 pathways. Key nodes include HSI appearing thirteen times in climate risk pathways, SH thirteen times, HSI ten times, and DAX four times in temperature risk pathways, SZ fourteen times, HSI eleven times, and DAX three times in drought risk pathways, and SZ fifteen times, HSI twelve times, and DAX four times in precipitation risk pathways. Again, the transmission sequence follows the order of drought risk, precipitation risk, climate risk, and temperature risk, except for temperature risk, which is initially transmitted directly through the wave source.

In summary, the transmission sequence of the four climate risks to representative stock markets remains consistent, with drought risk propagating first, followed by precipitation risk, climate risk, and finally temperature risk. It's crucial to note that the pivotal nodes differ among the pathways through which these risks transmit to representative stock markets. Specifically, for climate risk, monitoring the HSI, DAX, and SZ markets is paramount, while for temperature risk, additional vigilance should be placed on the SH and RTS markets. Drought risk and precipitation risk pathways share similar key nodes, including the SZ, HSI, and DAX markets.

5. Conclusion

This study delves into the propagation of climate risks across global stock markets through the Ripple-Spreading Network Model, examining both temporal and spatial dimensions. Notably, we consider three prevalent climate risk variables: drought, precipitation, and temperature risks, along with an overall index derived from a broader set of indicators.

Our findings underscore the substantial impact of climate risks on global stock markets, with initial penetration into Asian markets, followed by Europe and eventually the Americas. Moreover, climate risks

typically exhibit delayed onset in reaching stock markets but rapidly disseminate once introduced, albeit with diminishing propagation velocity. These dynamic transmission patterns hold true across all four types of climate risks.

Furthermore, we discern disparities in climate risk transmission across different timeframes. Notably, the short-term horizon witnesses a broader risk spread, affecting a greater number of stock markets, followed by the medium-term, and finally, the long-term, which exhibits the fewest affected markets. Additionally, the short-term timeframe experiences the swiftest risk propagation and boasts the highest number of transmission pathways among representative stock markets.

Moreover, distinctions emerge in the transmission dynamics of the four climate risks across global stock markets. Climate risk exerts the most widespread influence, followed by drought and precipitation risks, with temperature risk exhibiting the least impact. In terms of transmission speed, drought risk precedes precipitation risk, followed by climate risk, and finally temperature risk. Regarding transmission pathways, climate risk predominantly propagates through the HSI market (Hong Kong, China), DAX market (Germany), and SZ market (China), whereas temperature risk primarily spreads via the SH market (China), HSI market, DAX market, and RTS market (Russia). Drought and precipitation risks mainly disseminate through the SZ market, HSI market, and DAX market.

Our findings provide important insights for market participants in risk management and decision-making. Market participants should engage in targeted risk management strategies based on the specific characteristics of climate risks, such as their impact range, propagation speed, and transmission pathways. Short-horizon investors should be more attentive to climate risks, and promptly adjust their investment decisions to engage in targeted risk management. Additionally, investors and regulators should pay closer attention to the faster spreading and wider impact of drought and precipitation risks. It is also crucial to monitor the key markets in the transmission of different timescales and types of climate risks. For example, the HSI market (Hong Kong, China), DAX market (Germany), SZ market (China), and SH market (China) are crucial in the transmission of different types and timescales of climate risks. Monitoring these markets and their responses to climate risks is essential for effective risk management. Moreover, investors and regulators should encourage companies to disclose their exposure to climate risks and develop guidelines for reporting and assessing climate risk. This will enable investors to make informed decisions and encourage companies to implement measures for climate risk mitigation. Overall, understanding the transmission patterns and characteristics of climate risks among global stock markets can help market participants make more informed investment decisions and enhance risk management practices in the face of climate change challenges.

CRedit authorship contribution statement

Libo Yin: Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.
Hong Cao: Data curation, Software, Writing – original draft.

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Appendix A. The distance between climate risk and financial markets

Table A1

Market distance between overall climate risk and financial stock markets.

	Climate risk	APX	DJI	IXI	IBO	SH	SZ	TW	HSI	KS	N225	SEN	DAX	CAC	FTS	RTS	AS
Climate risk	0.00	100.25	95.42	222.52	89.09	65.04	70.01	85.97	49.71	85.38	357.70	66.01	56.05	114.98	68.00	115.68	568.65
APX	100.25	0.00	1.04	1.13	2.67	37.37	21.89	10.18	5.45	6.91	6.99	6.53	1.86	1.91	1.94	4.41	5.52
DJI	95.42	1.04	0.00	1.26	2.75	36.94	22.78	10.42	5.38	6.93	6.81	6.38	1.86	1.91	1.94	4.39	5.19
IXI	222.52	1.13	1.26	0.00	2.89	35.10	21.35	9.18	5.46	6.79	7.33	7.46	2.03	2.17	2.28	4.90	6.49
IBO	89.09	2.67	2.75	2.89	0.00	33.13	19.18	12.73	6.14	7.47	10.22	7.65	3.62	3.55	3.69	5.68	7.34
SH	65.04	37.37	36.94	35.10	33.13	0.00	1.44	10.44	5.28	11.12	9.06	9.70	16.40	16.80	15.56	15.87	7.50
SZ	70.01	21.89	22.78	21.35	19.18	1.44	0.00	8.56	4.16	8.50	7.53	9.74	13.49	12.61	12.82	14.40	6.92
TW	85.97	10.18	10.42	9.18	12.73	10.44	8.56	0.00	2.88	2.90	3.16	5.27	4.96	5.05	5.25	5.43	3.27
HSI	49.71	5.45	5.38	5.46	6.14	5.28	4.16	2.88	0.00	2.38	2.18	3.35	2.74	2.85	2.73	3.08	1.99
KS	85.38	6.91	6.93	6.79	7.47	11.12	8.50	2.90	2.38	0.00	2.66	4.22	4.08	4.11	3.89	4.39	2.65
N225	357.70	6.99	6.81	7.33	10.22	9.06	7.53	3.16	2.18	2.66	0.00	4.90	3.60	3.38	3.35	4.50	2.12
SEN	66.01	6.53	6.38	7.46	7.65	9.70	9.74	5.27	3.35	4.22	4.90	0.00	4.28	4.03	4.06	4.23	3.79
DAX	56.05	1.86	1.86	2.03	3.62	16.40	13.49	4.96	2.74	4.08	3.60	4.28	0.00	1.18	1.32	2.68	3.23
CAC	114.98	1.91	1.91	2.17	3.55	16.80	12.61	5.05	2.85	4.11	3.38	4.03	1.18	0.00	1.20	2.62	3.12
FTS	68.00	1.94	1.94	2.28	3.69	15.56	12.82	5.25	2.73	3.89	3.35	4.06	1.32	1.20	0.00	2.52	2.88
RTS	115.68	4.41	4.39	4.90	5.68	15.87	14.40	5.43	3.08	4.39	4.50	4.23	2.68	2.62	2.52	0.00	3.51
AS	568.65	5.52	5.19	6.49	7.34	7.50	6.92	3.27	1.99	2.65	2.12	3.79	3.23	3.12	2.88	3.51	0.00

Notes: This table represents the market distance between overall climate risk and financial stock markets. The tickers correspond to those in [Table 2](#).

Table A2

Market distance between temperature risk and financial stock markets.

	Temperature risk	APX	DJI	IXI	IBO	SH	SZ	TW	HSI	KS	N225	SEN	DAX	CAC	FTS	RTS	AS
Temperature risk	0.00	1760.60	166.22	93.42	1718.10	58.77	1504.65	812.27	161.68	6367.51	108.05	93.23	258.42	169.01	18,685.90	64.42	2545.67
APX	1760.60	0.00	1.04	1.13	2.67	37.37	21.89	10.18	5.45	6.91	6.99	6.53	1.86	1.91	1.94	4.41	5.52
DJI	166.22	1.04	0.00	1.26	2.75	36.94	22.78	10.42	5.38	6.93	6.81	6.38	1.86	1.91	1.94	4.39	5.19
IXI	93.42	1.13	1.26	0.00	2.89	35.10	21.35	9.18	5.46	6.79	7.33	7.46	2.03	2.17	2.28	4.90	6.49
IBO	1718.10	2.67	2.75	2.89	0.00	33.13	19.18	12.73	6.14	7.47	10.22	7.65	3.62	3.55	3.69	5.68	7.34
SH	58.77	37.37	36.94	35.10	33.13	0.00	1.44	10.44	5.28	11.12	9.06	9.70	16.40	16.80	15.56	15.87	7.50
SZ	1504.65	21.89	22.78	21.35	19.18	1.44	0.00	8.56	4.16	8.50	7.53	9.74	13.49	12.61	12.82	14.40	6.92
TW	812.27	10.18	10.42	9.18	12.73	10.44	8.56	0.00	2.88	2.90	3.16	5.27	4.96	5.05	5.25	5.43	3.27
HSI	161.68	5.45	5.38	5.46	6.14	5.28	4.16	2.88	0.00	2.38	2.18	3.35	2.74	2.85	2.73	3.08	1.99
KS	6367.51	6.91	6.93	6.79	7.47	11.12	8.50	2.90	2.38	0.00	2.66	4.22	4.08	4.11	3.89	4.39	2.65
N225	108.05	6.99	6.81	7.33	10.22	9.06	7.53	3.16	2.18	2.66	0.00	4.90	3.60	3.38	3.35	4.50	2.12
SEN	93.23	6.53	6.38	7.46	7.65	9.70	9.74	5.27	3.35	4.22	4.90	0.00	4.28	4.03	4.06	4.23	3.79
DAX	258.42	1.86	1.86	2.03	3.62	16.40	13.49	4.96	2.74	4.08	3.60	4.28	0.00	1.18	1.32	2.68	3.23
CAC	169.01	1.91	1.91	2.17	3.55	16.80	12.61	5.05	2.85	4.11	3.38	4.03	1.18	0.00	1.20	2.62	3.12
FTS	18,685.90	1.94	1.94	2.28	3.69	15.56	12.82	5.25	2.73	3.89	3.35	4.06	1.32	1.20	0.00	2.52	2.88
RTS	64.42	4.41	4.39	4.90	5.68	15.87	14.40	5.43	3.08	4.39	4.50	4.23	2.68	2.62	2.52	0.00	3.51
AS	2545.67	5.52	5.19	6.49	7.34	7.50	6.92	3.27	1.99	2.65	2.12	3.79	3.23	3.12	2.88	3.51	0.00

Notes: This table represents the market distance between temperature risk and financial stock markets. The tickers correspond to those in Table 2.

Table A3

Market distance between drought risk and financial stock markets.

	Drought risk	APX	DJI	IXI	IBO	SH	SZ	TW	HSI	KS	N225	SEN	DAX	CAC	FTS	RTS	AS
Drought risk	0.00	94.25	242.97	73.51	331.40	33.81	28.10	114.12	250.12	106.56	176.28	94.43	60.26	110.06	310.20	273.77	326.43
APX	94.25	0.00	1.04	1.13	2.67	37.37	21.89	10.18	5.45	6.91	6.99	6.53	1.86	1.91	1.94	4.41	5.52
DJI	242.97	1.04	0.00	1.26	2.75	36.94	22.78	10.42	5.38	6.93	6.81	6.38	1.86	1.91	1.94	4.39	5.19
IXI	73.51	1.13	1.26	0.00	2.89	35.10	21.35	9.18	5.46	6.79	7.33	7.46	2.03	2.17	2.28	4.90	6.49
IBO	331.40	2.67	2.75	2.89	0.00	33.13	19.18	12.73	6.14	7.47	10.22	7.65	3.62	3.55	3.69	5.68	7.34
SH	33.81	37.37	36.94	35.10	33.13	0.00	1.44	10.44	5.28	11.12	9.06	9.70	16.40	16.80	15.56	15.87	7.50
SZ	28.10	21.89	22.78	21.35	19.18	1.44	0.00	8.56	4.16	8.50	7.53	9.74	13.49	12.61	12.82	14.40	6.92
TW	114.12	10.18	10.42	9.18	12.73	10.44	8.56	0.00	2.88	2.90	3.16	5.27	4.96	5.05	5.25	5.43	3.27
HSI	250.12	5.45	5.38	5.46	6.14	5.28	4.16	2.88	0.00	2.38	2.18	3.35	2.74	2.85	2.73	3.08	1.99
KS	106.56	6.91	6.93	6.79	7.47	11.12	8.50	2.90	2.38	0.00	2.66	4.22	4.08	4.11	3.89	4.39	2.65
N225	176.28	6.99	6.81	7.33	10.22	9.06	7.53	3.16	2.18	2.66	0.00	4.90	3.60	3.38	3.35	4.50	2.12
SEN	94.43	6.53	6.38	7.46	7.65	9.70	9.74	5.27	3.35	4.22	4.90	0.00	4.28	4.03	4.06	4.23	3.79
DAX	60.26	1.86	1.86	2.03	3.62	16.40	13.49	4.96	2.74	4.08	3.60	4.28	0.00	1.18	1.32	2.68	3.23
CAC	110.06	1.91	1.91	2.17	3.55	16.80	12.61	5.05	2.85	4.11	3.38	4.03	1.18	0.00	1.20	2.62	3.12
FTS	310.20	1.94	1.94	2.28	3.69	15.56	12.82	5.25	2.73	3.89	3.35	4.06	1.32	1.20	0.00	2.52	2.88
RTS	273.77	4.41	4.39	4.90	5.68	15.87	14.40	5.43	3.08	4.39	4.50	4.23	2.68	2.62	2.52	0.00	3.51
AS	326.43	5.52	5.19	6.49	7.34	7.50	6.92	3.27	1.99	2.65	2.12	3.79	3.23	3.12	2.88	3.51	0.00

Notes: This table represents the market distance between drought risk and financial stock markets. The tickers correspond to those in [Table 2](#).

Table A4

Market distance between precipitation risk and financial stock markets.

	Precipitation risk	APX	DJI	IXI	IBO	SH	SZ	TW	HSI	KS	N225	SEN	DAX	CAC	FTS	RTS	AS
Precipitation risk	0.00	70.26	118.71	62.16	1293.66	41.69	30.98	99.86	341.78	135.88	256.51	121.12	67.86	127.87	561.24	1739.31	426.16
APX	70.26	0.00	1.04	1.13	2.67	37.37	21.89	10.18	5.45	6.91	6.99	6.53	1.86	1.91	1.94	4.41	5.52
DJI	118.71	1.04	0.00	1.26	2.75	36.94	22.78	10.42	5.38	6.93	6.81	6.38	1.86	1.91	1.94	4.39	5.19
IXI	62.16	1.13	1.26	0.00	2.89	35.10	21.35	9.18	5.46	6.79	7.33	7.46	2.03	2.17	2.28	4.90	6.49
IBO	1293.66	2.67	2.75	2.89	0.00	33.13	19.18	12.73	6.14	7.47	10.22	7.65	3.62	3.55	3.69	5.68	7.34
SH	41.69	37.37	36.94	35.10	33.13	0.00	1.44	10.44	5.28	11.12	9.06	9.70	16.40	16.80	15.56	15.87	7.50
SZ	30.98	21.89	22.78	21.35	19.18	1.44	0.00	8.56	4.16	8.50	7.53	9.74	13.49	12.61	12.82	14.40	6.92
TW	99.86	10.18	10.42	9.18	12.73	10.44	8.56	0.00	2.88	2.90	3.16	5.27	4.96	5.05	5.25	5.43	3.27
HSI	341.78	5.45	5.38	5.46	6.14	5.28	4.16	2.88	0.00	2.38	2.18	3.35	2.74	2.85	2.73	3.08	1.99
KS	135.88	6.91	6.93	6.79	7.47	11.12	8.50	2.90	2.38	0.00	2.66	4.22	4.08	4.11	3.89	4.39	2.65
N225	256.51	6.99	6.81	7.33	10.22	9.06	7.53	3.16	2.18	2.66	0.00	4.90	3.60	3.38	3.35	4.50	2.12
SEN	121.12	6.53	6.38	7.46	7.65	9.70	9.74	5.27	3.35	4.22	4.90	0.00	4.28	4.03	4.06	4.23	3.79
DAX	67.86	1.86	1.86	2.03	3.62	16.40	13.49	4.96	2.74	4.08	3.60	4.28	0.00	1.18	1.32	2.68	3.23
CAC	127.87	1.91	1.91	2.17	3.55	16.80	12.61	5.05	2.85	4.11	3.38	4.03	1.18	0.00	1.20	2.62	3.12
FTS	561.24	1.94	1.94	2.28	3.69	15.56	12.82	5.25	2.73	3.89	3.35	4.06	1.32	1.20	0.00	2.52	2.88
RTS	1739.31	4.41	4.39	4.90	5.68	15.87	14.40	5.43	3.08	4.39	4.50	4.23	2.68	2.62	2.52	0.00	3.51
AS	426.16	5.52	5.19	6.49	7.34	7.50	6.92	3.27	1.99	2.65	2.12	3.79	3.23	3.12	2.88	3.51	0.00

Notes: This table represents the market distance between precipitation risk and financial stock markets. The tickers correspond to those in [Table 2](#).

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eneco.2024.107445>.

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