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# Assessing the complex dynamics of climate risk on tourism stock performance: insights from European and US markets

**Zhaobin Yang[1], Hongjun Zeng[2]**, Feini Liu[3] and Ran Wu[4]**
[1]School of Law, Wuhan University, Wuhan, China
[2]Department of financial planning and tax School of Accounting, Information Systems and Supply Chain
[3]College of Economics and Management Nanjing Agricultural University, Nanjing 210095, China
[4]School of Economics and Management Southeast University, Nanjing, China
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*to whom all correspondence should be addressed: e-mail: hongjun.zeng@student.rmit.edu.au
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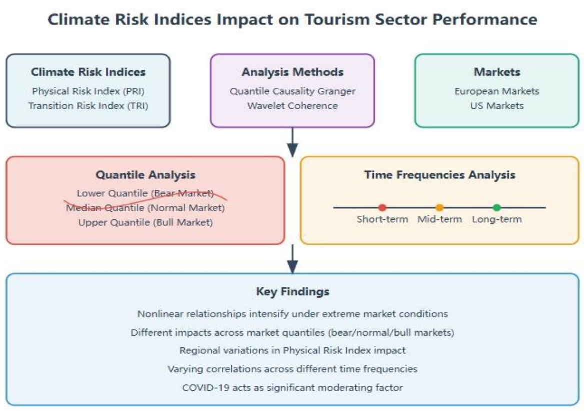
## Graphical abstract




## Abstract

This study systematically examines the linear and nonlinear relationships between the Climate Physical Risk Index (PRI), Transition Risk Index (TRI), and the stock performance of the tourism sector in European and American stock markets from 2015 to 2022, using Quantile Granger Causality and Wavelet Coherence Analysis methods. The results show a complex nonlinear relationship between the climate risk indices used and the performance of the tourism sector in European and American stock markets. Specifically, the impact of PRI is found to have regional heterogeneity and time-varying effects, with significant correlations across multiple time scales. Furthermore, we find that the correlation patterns of TRI vary at different frequencies. Additionally, we identify COVID-19 as an important exogenous shock factor influencing these correlation patterns. Our findings provide valuable insights for investment and business decisions, as well as policy formulation, for practitioners, investors, and policymakers in the European and American tourism sectors.

**Keywords:** climate risk; tourism sectors; Physical Risk Index; Transition Risk Index

## 1. Introduction

At present, climate change is regarded as one of the top global challenges facing mankind in the 21st century (Zeng *et al.*, 2024a). As the global average temperature continues to rise and extreme weather events become more frequent, sea levels are gradually rising and ecosystem degradation is intensifying. The above series of environmental changes are profoundly affecting the healthy and stable development of the global economy and society (Zeng *et al.*, 2023; Wu *et al.*, 2024). In this context, it is becoming increasingly important to accurately measure and assess the impact of climate change risks on relevant industries. It is worth emphasizing that as an important pillar of the global national economic system, the tourism industry is particularly vulnerable to the impact of climate change due to its high sensitivity to the environment and climate change (Lu *et al.*, 2023; Li *et al.*, 2024).

The research of Lenzen *et al.* (2018) confirmed that the role of tourism in promoting climate change cannot be underestimated. Carbon emissions from the tourism industry account for about 8% of the global total. At the same time, the tourism industry is also one of the main industries affected by climate change. Becken and Hay (2007) pointed out that the impact of climate change on the tourism industry is multidimensional: there are direct physical consequences, such as rising sea levels threatening coastal tourist destinations; there are also indirect environmental effects, such as reduced biodiversity weakening the attractiveness of the ecotourism industry; there may also be broader socioeconomic impacts, such as the implementation of climate policies that may increase potential travel costs.

In recent years, relevant research has explored the relationship between climate change and the tourism industry more deeply. Scott *et al.* (2012) comprehensively reviewed the impact of climate change on the tourism industry. The study showed that the spillover effect of climate impacts will significantly change the attractiveness of tourist destinations, the travel habits of potential tourist groups, and the seasonal characteristics of tourism and ancillary industries. Dogru *et al*. (2019) investigated the vulnerability and resilience of the tourism sector to climate change, finding that climate change directly impacts tourism while also indirectly influencing tourism demand through its effects on the overall economy. Rosselló-Nadal (2014) proposed a methodological framework for assessing the impacts of climate change on tourism, emphasizing the importance of considering the multidimensional nature of climate change. Furthermore, Fang *et al*. (2018) conducted a bibliometric analysis that revealed key themes and trends in climate change and tourism research, providing guidance for future research directions.

Despite the valuable insights provided by existing studies, significant research gaps remain. First, most studies focus on the physical risks of climate change, while there is relatively less attention on transition risks associated with the shift to a low-carbon economy. Second, existing research often concentrates on specific countries or regions, lacking systematic comparisons among major tourism nations and regions. Additionally, research on the relationship between climate risks and tourism stock market performance is limited, especially concerning dynamic relationships under varying market conditions.

In light of this, the present work aims to check the impact of climate risk indices on the tourism sectors of stock markets in EU and the US, focusing specifically on the United States, the United Kingdom, and the European Union. Specifically, this study seeks to answer the following questions: (1) Is there a significant association between climate risk indices and the performance of tourism stocks? (2) Are there differences in this association across different countries and regions? (3) Does the impact of climate risks on tourism stock markets vary over time and under different market conditions?

To address these questions, this study will employ an innovative combination of methodologies. First, we will utilize wavelet coherence analysis to explore the time-frequency domain relationship between climate risk indices and tourism stock indices. Unlike traditional time-series methods such as vector autoregression (VAR) or simple correlation analysis which assume stable relationships over time, wavelet coherence analysis offers unique advantages in capturing dynamic, time-varying relationships. While GARCH models could analyze time-varying volatility, they cannot simultaneously examine different time horizons, making wavelet analysis particularly suitable for our multi-scale investigation. This method can capture the connection between two variables at different time scales, thus helping us to gain a deeper understanding of the specific manifestations of the impact patterns at different frequencies. second, we will apply the Quantile Granger Causality check to examine the nonlinear impacts of climate risks on tourism stock markets. Although standard Granger causality tests and regime-switching models could also detect nonlinear relationships, they either assume constant parameters across different market conditions or require pre-specified regime thresholds. The advantage of the quantile correlation method is that it allows the correlation between different variables to be flexibly adjusted as market conditions change without rigidly imposing restrictive assumptions. In our study, the quantile correlation method can clearly show whether the impact of climate risk on European and American tourism industry stocks will change as the market environment changes. Of course, other nonlinear methods can also be considered, such as threshold regression or Markov switching models, but these methods often have to make conditional assumptions about the form of nonlinearity first, so in comparison, they may not be as flexible as quantile regression to cover possible changes in market conditions. Therefore, we combine these methods to not only make our analysis more comprehensive and detailed, but also jump out of the framework of traditional linear models and bring new research findings.

The theoretical value of this study is mainly reflected in three aspects: First, it combines climate risk research with financial market analysis, broadening the scope of climate finance research Second, through cross-national comparative analysis, this study reveals the regional disparities in the impact of climate risks, enriching the theoretical foundation of international tourism economics. Third, we shed new light on the interaction between climate risk and financial markets by employing a range of advanced econometric methods.

Practically, the findings of this study will provide important references for various stakeholders. For policymakers, the results can enhance their understanding of the potential impacts of climate policies on tourism, enabling them to develop more balanced and effective climate adaptation and mitigation strategies. For tourism enterprises and investors, this research will provide crucial insights for risk management and investment decisions, assisting them in optimizing ass*et al*location and operational strategies in the context of climate change. For tourism destination management organizations, the findings can guide the development of more resilient and sustainable development plans, enhancing their capacity to respond to climate risks.

Through Quantile Granger causality method and wavelet coherence test, this study delves into the relationship between climate risks and tourism stock performance. The results of the Quantile Granger causality analysis indicate a significant nonlinear relationship between climate risks (including physical risks and transition risks) and tourism stock performance, which is most pronounced under extreme market conditions (high and low quantiles) and insignificant under normal market conditions (around the median). Wavelet coherence analysis further reveals a complex dynamic connection between climate risks and tourism stocks across multiple time scales, showing significant correlations from short-term (4-16 days) to long-term (over 256 days), though these correlations exhibit clear differences across countries and time periods.

The findings also suggest that the mechanisms of impact for the Physical Risk Index (PRI) and the Transition Risk Index (TRI) on tourism stocks differ, with such impacts being prevalent across Europe and the United States. However, due to geographical, policy, and market structure differences, these impacts manifest in varied patterns across different countries. This finding emphasizes the importance of incorporating climate risks into investment decisions and policy formulation within the tourism sector, as well as the necessity of developing targeted strategies to address challenges posed by varying market conditions and types of climate risks.

The structure of this paper is organized as follows: The second section will review relevant literature, outlining the current state of research on the relationships among climate risks, tourism, and stock markets; the third section will detail the research methodology, including data sources, variable selection, and specific steps for wavelet coherence check and Granger Quantile causality testing; the fourth section will present the empirical analysis results and engage in in-depth discussion; the fifth section will summarize the research findings, propose policy recommendations, and identify future directions.

## 2. Literature review

The academic literature examining the intersection of climate risk and financial markets, particularly in the tourism sector, has evolved along several key theoretical and methodological dimensions. This development process exposed key deficiencies in the research, and the original intention of this study was to remedy these deficiencies.

The discussion on the impact of climate risk on financial markets mainly follows two theoretical lines. The first line focuses on physical climate risk. Weir (2017) found that climate change significantly weakened the attractiveness of tourist destinations, and this impact was ultimately reflected in the financial performance of tourism companies. Kang *et al*. (2015) analyzed the role of extreme weather events on US airline stock returns, documenting short-term price fluctuations and changes in investors' expectations for long-term prospects (Abedin *et al*. 2024). The second line focuses on transition risks. Battiston *et al*. (2017) constructed a climate stress test model to illustrate how a sudden shift in climate policy can induce systemic financial risks through asset depreciation (Zeng *et al*., 2024c; Wu *et al*., 2025).

In terms of methodology, relevant research has gradually shifted from early simple correlation analysis to more sophisticated tools. Balvers *et al*. (2017) used a panel data model to study the impact of temperature changes on stock returns, while Huynh and Xia (2021) used machine learning methods to construct a multidimensional climate risk index. More recent, Engle *et al*.'s (2020) "climate beta" indicator for asset pricing sensitivity and Giglio *et al*.'s (2021) multi-temporal analysis of climate risk impacts.

This methodological evolution has occurred alongside expanding market coverage. Chiang *et al*. (2017) studied tourism stocks in major European and American markets, highlighting their heightened volatility during economic uncertainty. However, this market focus reveals a significant geographical bias in existing research.

Through this systematic review, several critical research gaps emerge. First, while existing studies examine either physical or transition risks separately, there is limited research integrating both dimensions comprehensively. Second, despite evidence suggesting nonlinear relationships in climate-financial interactions, most studies employ linear methodologies. Third, while recent work acknowledges the time-varying nature of climate risk impacts, few studies have developed methodological frameworks capable of capturing these dynamics across different time scales. Fourth, cross-market comparative analyses remain scarce, limiting our understanding of geographical variations in climate risk impacts.

Our study addresses these gaps by: (1) simultaneously examining both physical and transition risks through our dual-index approach; (2) employing quantile Granger causality tests to capture nonlinear relationships; (3) utilizing wavelet coherence analysis to examine time-varying impacts across multiple scales; and (4) conducting a comparative analysis across major developed markets. This comprehensive approach enables us to provide a more nuanced understanding of how climate risks affect tourism stock markets, contributing both theoretically and methodologically to the existing literature.

## 3. Methodology

### *3.1. Quantile granger check*

This part aimed to offer a comprehensive overview of the Quantile Granger Causality assessment approach employed to scrutinise the causal nexus betwixt the Climate Risk Indexes and tourism sectors. The foundational notion of Granger causality posited that if a temporal sequence $X_t$ did not substantially enhance the forecasting of another temporal sequence $Y_t$, then $X_t$ did not Granger cause $Y_t$. In pragmatic implementations, it was imperative to suitably calibrate the temporal junctures $t$ in accordance with the investigative aspirations. To evaluate the causality betwixt Climate Risk Indexes and tourism sectors, we initially needed to delineate the dual temporal sequences $X_tY_t$ (at the equivalent sample $t$). Then an explanatory function $I_t \underline{\underline{\mathrm{def}}} \left(I_t^Y, I_t^X\right)' \in R^d, d = s + q. I_t^X$ is the information set of $X_t$, $I_t^X := \left(\overline{X_{t-1}}, \ldots, X_{t-q}\right)' \in R^q$. The null hypothesis:

$$H_0 : F_Y\left(y | I_t^Y, I_t^X\right) = F_Y\left(y | I_t^Y\right). \forall y \in R. \quad (1)$$

Where, $F_Y(y|.)$ offers the distribution of conditional of detail $(I_t^Y, I_t^X)$. $X_t$ isn't Granger-cause $Y_t$ if:

$$E\left(Y_t | I_t^Y, I_t^X\right) = E\left(Y | I_t^Y\right), \text{ a.s.} \quad (2)$$

where $E\ (Y_t | I_t^Y, I_t^X)$ and $E\ (Y | I_t^Y)$ are the mean amounts of $(I_t^Y, I_t^X)$ and $(Y | I_t^Y)$, respectively. If we let $Q_T^Y, X\ (. | I_t^Y, I_t^X)$ as the τ-quantile of $F_Y\ (. | I_t^Y, I_t^X)$, then we will have the amount of $Q_T^Y(. | I_t^Y)$.

Then $T$ indicates to the set $T \in [0, 1]$:

$$H_O : Q_\tau^{Y,X}\left(Y_t | I_t^Y, I_t^X\right) = Q_\tau^Y\left(Y_t | I_t^Y\right), \text{ a.s. } \forall \tau \in \mathrm{T}. \quad (3)$$

The specify $\tau$-quantile of $Y_t$ meets:

$$\begin{aligned} &\Pr\left\{Y_t \le Q_T^Y\left(Y_t | I_t^Y\right) | I_t^Y\right\} := \tau, \text{ a.s.} \forall \tau \in \mathrm{T}, \\ &\Pr\left\{Y_t \le Q_T^{Y,X}\left(Y_t | I_t^Y, I_t^X\right) | I_t^Y, I_t^X\right\} := \tau, \text{a.s.} \forall \tau \in \mathrm{T}, \end{aligned} \quad (4)$$

For independent variable $I_t$, the probability $\Pr\left\{Y_t \le Q_T\left(Y_t | I_t\right) | I_t\right\} = E\left\{1\left[Y_t \le Q_T\left(Y_t | I_t\right)\right] | I_t\right\}$. Then a function of $1[Y_t \le Y]$. The null hypothesis is:

$$E\left\{1\left[Y_t \le Q_T^{Y,X}\left(Y_t | I_t^Y, I_t^X\right)\right] | I_t^Y, I_t^X\right\} = E\left\{1\left[Y_t \le Q_T^Y\left(Y_t | I_t^Y\right)\right] | I_t^Y\right\}, \text{ a.s. } \forall \tau \in \mathrm{T}. \quad (5)$$

Assuming that $Q_T(.|I_t)$ is specified via a parametric structure that provides to a set of functions difined by $M = \left\{m\left(.| \theta(\tau)\right) | \theta(.) : .\tau \to \theta(\tau) \in \Theta \subset R^p\right\}$, hence the Granger non-causality connection:

$$H_O : E\left\{1\left[Y_t \le m\left(I_t^Y, \theta_0(\tau)\right)\right] | I_t^Y, I_t^X\right\} = \tau, \text{ a.s. } \forall \tau \in \mathrm{T}. \quad (6)$$

where $m\ (I_t^Y,\ \theta_0(\tau))$ is the quantile for $Q_T^Y(.|I_t^Y)$. The null hypothesis as:

$$E\left\{1\left[Y_t - m\left(I_t^Y, \theta_0(\tau)\right) \le 0\right] - \tau\right\} \exp\left(i\omega' I_t\right)\Big\} = 0. \quad (7)$$

As the test of Troster (2018):

$$\begin{aligned} &P_T := \iint_{\tau\, Z} \left|v_T(\omega,\tau)\right|^2 dF_\omega(\omega) dF_\tau(\tau), \\ &v_T(\omega,\tau) := \frac{1}{\sqrt{T}} \sum_{t=1}^{T} \left\{1\left[Y_t - m\left(I_t^Y, \theta_0(\tau)\right) \le 0\right] - \tau\right\} \exp\left(i\omega' I_t\right). \end{aligned} \quad (8)$$

Let $\phi_{\tau_j}(.)$ be the framework such that $\phi_{\tau_j}(\varepsilon) = 1(\varepsilon \le 0)$, the evaluation of statistics as:

$$P_T = \frac{1}{Tn} \sum_{j=1}^{n} \left|\vartheta_j' Z \vartheta_j\right| \quad (9)$$

where $Z$ is a $T \times T$ matrix, and $\vartheta_j$ indicates the $j$ th column of $\phi$.

*3.2. Wavelet coherence method*

In accordance with the characterisation propounded by Torrence and Compo (1998), and WC is,

$$R_{xy}^2(a,b) = \frac{\left|S\left(b^{-1}W_{xy}(a,b)\right)\right|^2}{S\left(b^{-1}W_x(a,b)\right)^2 S\left(b^{-1}W_y(a,b)\right)^2} \quad (10)$$

where $W_{xy}\ (a,\ b) = W_x\ (a,\ b)\ Wy\ (a,\ b)$ is indicated the wavelet transform and $S$ denotes the smoothing parameter, $0 \le R_{xu}^2$ (a, b)$\le 1$.

The subsequent step involved calculating the phase discrepancy in the wavelet as,

$$\phi_{xy} = arctan\left(\frac{Im\left[S\left(b^{-1}W_{xy}(a,b)\right)\right]}{Re\left[S\left(b^{-1}W_{xy}(a,b)\right)\right]}\right), with\, \phi_{xy} \in [-\pi, \pi] \quad (11)$$

In the preceding equation, *Im* and *Re* represented the imaginary component and real component of the power spectrum in smoothed, correspondingly. The phase $\phi_{xy}$ offered understandings into the connection and prospective leading-lag nexus betwixt two indices.

## 4. Empirical analysis

This study selects the tourism sectors of the UK, US, and EU stock markets as representatives to reflect the market performance of major tourism industries in developed countries. This choice is based on the significant role these countries and regions play in the global tourism industry, as well as the maturity and representativeness of their financial markets. Specifically, these markets collectively account for over 45% of global tourism receipts and represent more than 60% of the world's tourism-related market capitalization. We used relevant sector indices provided by the Datastream database, which comprehensively reflect the overall market performance of publicly listed companies related to tourism in these countries. These indices track the performance of companies deriving at least 50% of their revenue from tourism-related activities, including hotels, airlines, cruise lines, and travel services. As a leading global financial data provider, Datastream's reliability and comprehensiveness provide a solid foundation for this research.

At the same time, to measure the potential impact of climate change on the tourism industry, we introduced two key indicators: the Climate Transition Risk Index (TRI) and the Physical Climate Risk Index (PRI). The TRI and PRI are calculated as a composite score based on three components: carbon pricing pressure, regulatory policy changes, and technological transition costs. The Climate Transition Risk primarily reflects the potential impacts on businesses and industries during the transition to a low-carbon economy, such as policy changes and technological innovations. Physical climate risk is directly related to the potential impact of extreme weather events, sea level rise, and other physical phenomena caused by climate change on the tourism industry. Data for these two indicators come from the EPU website.

Our research covers daily data from January 1, 2014 to April 1, 2023. This span is long enough to reflect long-term trends and cyclical laws, while capturing the latest market dynamics, ensuring that the research conclusions are both relevant and not outdated. In addition, the starting point of 2014 coincides with the implementation of major climate policies in the sample region, including the EU's 2030 Climate and Energy Framework and the US's Clean Power Plan, providing a natural experimental environment for the analysis of transition risks. In preprocessing the data, we removed missing values to maintain the consistency of the data while mitigating the impact of extreme values.

**Table 1** presents descriptive statistics for the Climate Risk Index (TRI and PRI) and the tourism sectors of the US, UK, and Eurozone stock markets. We can analyze these data from several perspectives.

First, the mean values indicate the overall trends in the data. The means of the PRI and TRI are -0.002123 and -0.003667, respectively, suggesting that the climate risk-related indices averaged negative values during the sample period, reflecting certain risk impacts. In contrast, the mean values for the stock market tourism sectors vary between the US (-0.00195), UK (-0.029937), and Eurozone (0.006703), indicating differing sensitivities to risk among markets, particularly a slight positive trend in the Eurozone.

**Table 1.** Descriptive statistics

| | PRI | TRI | UK | US | EURO |
|---|---|---|---|---|---|
| Mean | -0.002123 | -0.003667 | -0.00195 | -0.029937 | 0.006703 |
| Median | -0.00435 | -0.005747 | 0.045102 | 0.041405 | 0.019998 |
| Maximum | 0.122507 | 0.137991 | 11.56337 | 18.25744 | 9.583606 |
| Minimum | -0.055995 | -0.078206 | -14.65536 | -80.03126 | -14.26429 |
| Std. Dev. | 0.02052 | 0.021537 | 1.631397 | 3.18893 | 1.646749 |
| Skewness | 0.835234 | 0.701107 | -0.468686 | -8.153154 | -0.626708 |
| Kurtosis | 4.912346 | 5.49549 | 14.59697 | 200.311 | 11.47968 |
| Jarque-Bera | 574.3675*** | 729.9199*** | 12059.06*** | 3491847*** | 6545.494*** |
| ADF | -14.943*** | -12.502*** | -42.157*** | -20.349*** | -43.069*** |

*Notes: *, ** and *** indicate 10%, 5%, and 1% significance levels, respectively*

Second, the maximum and minimum values reveal the range of fluctuations for these variables. The maximum and minimum values for PRI and TRI are relatively small, at 0.122507 and -0.055995, as well as 0.137991 and -0.078206, indicating that the climate risk indices are relatively stable. In comparison, the volatility of the tourism sectors in the US, UK, and Eurozone stock markets is significantly greater, especially in the US, where the maximum value reaches 11.56337 and the minimum is -14.65536, showing considerable market fluctuations during the sample period.

The standard deviation further elucidates volatility, with relatively low standard deviations for TRI and PRI at 0.021537 and 0.02052, respectively, while the stock market sectors exhibit higher values, particularly in the US market (1.631397) and the Eurozone (3.18893), reflecting the high volatility characteristic of these markets.

Skewness and kurtosis provide additional insights into the data distribution. The skewness of the climate risk indices is positive, indicating a right-skewed distribution, while the skewness for the UK and US markets is negative, indicating a left-skewed distribution, particularly evident in the US market with a skewness of -8.153154, reflecting an abnormal left tail phenomenon. Regarding kurtosis, the values for the climate risk indices exceed 3, indicating a distribution with heavy tails and peaks, especially with the US market showing a kurtosis of 200.311, suggesting a tendency for extreme fluctuations.

Finally, the Jarque-Bera statistic and its corresponding significance levels indicate that all variables significantly deviate from normal distribution, particularly the stock market sectors, which have statistics far exceeding those of the climate risk indices, demonstrating greater asymmetry in the market. The ADF test results indicate that all time series reject the unit root hypothesis at the 1%, 5%, and 10% significance levels, suggesting that these data represent stationary time series.

Overall, the table highlights the differences in volatility, distribution characteristics, and stationarity between the climate risk indices and the tourism markets, with the latter exhibiting greater fluctuations and non-normal distribution features, while the climate risk indices remain relatively stable.

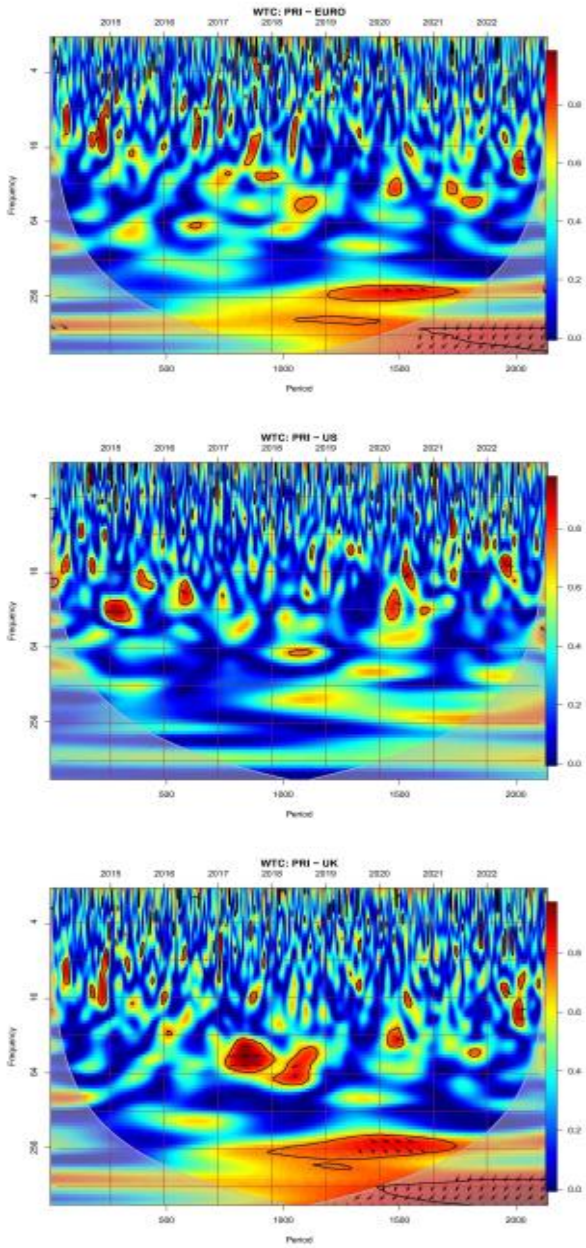



**Figure 1.** wavelet coherence of PRI and Euro and US market

**Tables 2 and 3** reveal the complex relationships between the PRI and the TRI with the tourism sectors of major national stock markets, showing significant nonlinear characteristics under different market conditions.

The quantile analysis suggests varying associations between climate risk indices and tourism sectors under extreme market conditions (i.e., when the quantile q is close to 0 or 1). These stronger statistical relationships may reflect an increased sensitivity of market participants to climate risks in the face of extreme situations. For instance, during market downturns (low quantiles), investors may be more focused on the additional pressures that climate risks could impose; conversely, in times of market prosperity (high quantiles), climate risks might be perceived as potential constraints on growth or as opportunities.

It is noteworthy that near the median (q=0.5), the Granger causality is not significant. This statistical pattern suggests that under "normal" market conditions, climate risk factors could be less prominent compared to other more direct economic factors. This phenomenon is consistent with the "limited attention" theory in behavioral finance, suggesting that investors might overlook certain potentially important factors during ordinary times.

Our analysis indicates different patterns of association for physical risks (such as extreme weather events) and transition risks (such as policy changes) with the tourism industry. Physical risks could directly affect the attractiveness and infrastructure of tourist destinations, while transition risks may influence the tourism sector by altering operational costs for businesses and consumer behavior. These distinct patterns may help explain why these two types of risks exhibit different relationships under varying market conditions.

The consistency of results across different countries suggests that the relationship between climate risk and the tourism sector has a transatlantic nature. Overall, these findings emphasize the importance of considering climate risk in investment decisions and policy formulation in the tourism sector, particularly when examining extreme market scenarios.

**Table 2**. Checks for the TRI and the travel and leisure sectors

| | **TRI To** | | |
|---|---|---|---|
| ***τ*** | **UK** | **US** | **EURO** |
| All | 0.01*** | 0.01*** | 0.01*** |
| 0.05 | 0.01*** | 0.01*** | 0.01*** |
| 0.10 | 0.01*** | 0.01*** | 0.01*** |
| 0.25 | 0.01*** | 0.01*** | 0.01*** |
| 0.50 | 0.368 | 0.597 | 0.330 |
| 0.75 | 0.01*** | 0.01*** | 0.01*** |
| 0.90 | 0.01*** | 0.01*** | 0.01*** |
| 0.95 | 0.01*** | 0.01*** | 0.01*** |

*Note: The table displayed the uniform parameter assessment for Granger quantile causality.* τ *indicates quantile levels. *, **, and *** signified the 10%, 5%, and 1% significance thresholds, correspondingly.*

**Table 3**. Checks for PRI and the travel and leisure sectors

| | | ***TRI* to** | |
|---|---|---|---|
| ***τ*** | **UK** | | ***EURO*** |
| All | 0.01*** | 0.01*** | 0.01*** |
| 0.05 | 0.01*** | 0.01*** | 0.01*** |
| 0.10 | 0.01*** | 0.01*** | 0.01*** |
| 0.25 | 0.01*** | 0.01*** | 0.01*** |
| 0.50 | 0.366 | 0.599 | 0.329 |
| 0.75 | 0.01*** | 0.01*** | 0.01*** |
| 0.90 | 0.01*** | 0.01*** | 0.01*** |
| 0.95 | 0.01*** | 0.01*** | 0.01*** |

*Note: The table displayed the uniform parameter assessment for Granger quantile causality.* τ *indicates quantile levels. *, **, and *** signified the 10%, 5%, and 1% significance thresholds, correspondingly.*

In **Figure 1**, we first observe the dynamic connection between the PRI and the travel and leisure sector of the European stock market (EURO). The analysis reveals that their correlation exhibits complex patterns across different time scales and frequencies. At short-term frequencies (4-16 days), intermittent high correlation zones are evident throughout the study period, indicating an immediate impact of climate risk on tourism stocks. At medium-term frequencies (16-64 days), the correlation is more dispersed, with several significant high correlation areas emerging around 2018 and 2021, likely reflecting the influence of prolonged climate events during these periods. It is particularly noteworthy that at long-term frequencies (more than 256 days), there has been a persistent high correlation area since the end of 2019, and the correlation direction is downward. This indicates that during this period, the climate physical risk index has had a significant negative effect on the performance of European tourism stocks. This phenomenon is likely closely related to the public's deepening awareness of the worsening of climate change and its long-term impact on the tourism industry. Overall, this complex relationship pattern reveals the multi-scale impact of climate risk on the European tourism industry, both short-term weather events and long-term climate change trends, which have a significant impact on stock performance (Wang *et al*., 2025).

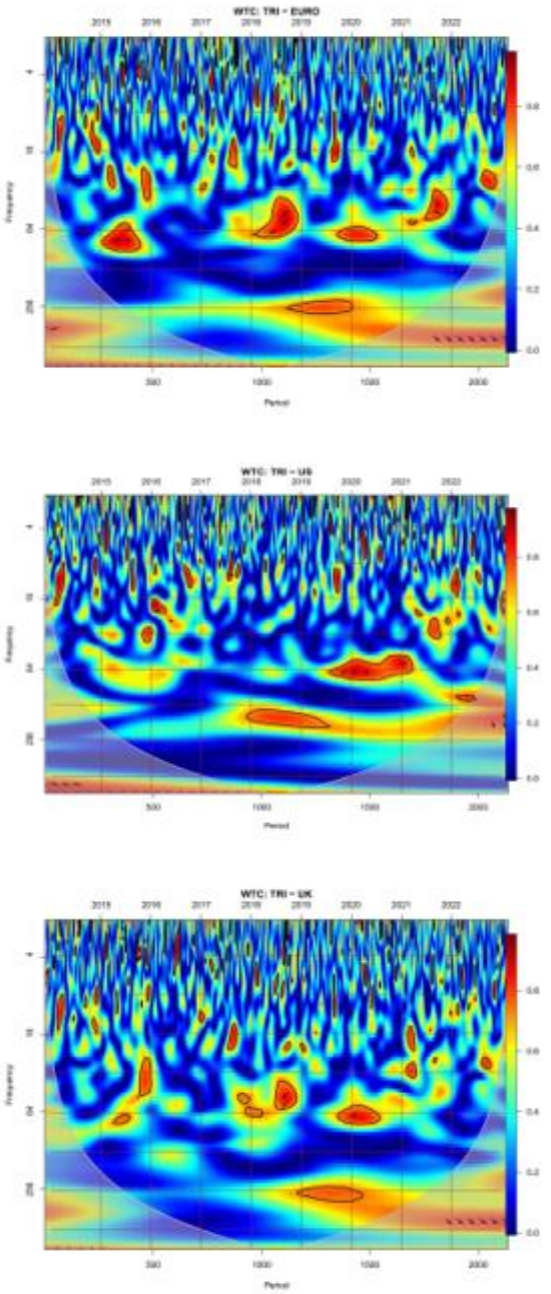



**Figure 2.** wavelet coherence of TRI and Euro and US market

Next, we explore the dynamic relationship between PRI and US. We note that the correlation between the two shows nonlinear and complex characteristics at different time scales and frequencies. Among them, in the short-term frequency range (4-16 days), multiple intermittent high correlation areas indicate that climate risks frequently impact US tourism stocks. The distribution of these high correlation areas (red areas in the figure) is relatively uniform, which can be considered that the US tourism industry is highly sensitive to short-term climate events. At medium-term frequencies (16-64 days), several significant high correlation zones are evident, particularly around late 2015 to early 2016 and around 2020, reflecting the longer-term impact of persistent climate events during those periods. Notably, unlike the European market, the U.S. market does not exhibit sustained high correlation zones at long-term frequencies (over 256 days), possibly indicating a stronger adaptive capacity of the U.S. tourism sector to long-term climate risks or differing perceptions among investors regarding the impact of long-term climate change on the U.S. tourism industry. Overall, this complex correlation pattern indicates that climate risk impacts on the U.S. tourism industry are primarily concentrated in the short- and medium-term, potentially reflecting structural characteristics of the U.S. tourism sector or differing investor perspectives on climate risks. Compared to the EU, U.S. tourism stocks appear to show different sensitivities to long-term climate risks, possibly due to geographical characteristics, climate policies, or investor behavior.

Lastly, we observe the dynamic connection between the PRI and the tourism sector of the UK stock market (UK). At short-term frequencies (4-16 days), multiple intermittent high correlation zones throughout the study period suggest that UK tourism stocks are sensitive to short-term climate events. This finding can be considered highly consistent with the characteristics of the US and European markets, indicating that the tourism industry is generally vulnerable to short-term weather fluctuations. Furthermore, in the medium-term frequency range (16-64 days), we observed several significant high correlation areas, especially in the period of 2017-2018, when a continuous high correlation interval clearly appeared. This may be related to specific climate events or seasonal anomalies experienced by the UK during this period, which had a more lasting impact on the local tourism industry (Zeng *et al*., 2025).

Particularly striking is that in the long-term frequency, from 2019 to the end of the study period, there is a strong high correlation area, and the correlation direction is downward. This phenomenon indicates that during this period, the Climate Physical Risk Index not only exhibited a high correlation with UK tourism stocks but also showed a leading and negative influence on them. This long-term, sustained high correlation pattern is similar to that observed in the European market but is more pronounced than in the U.S. market, possibly reflecting a higher sensitivity of UK and European investors to long-term climate change risks or specific climate challenges faced by the UK tourism sector (Wang *et al*., 2024).

It is also noteworthy that the graph displays a series of rightward-pointing arrows beginning in early 2020, suggesting that the performance of the tourism industry started to influence perceptions of climate risk amid the context of the COVID-19 pandemic, illustrating the complex bidirectional relationship between climate risk and the tourism sector.

Next, **Figure 2** illustrates the dynamic connections in the relationship between the TRI and the travel and leisure sector of the EURO from 2015 to 2022. The colors range from blue to red, indicating a transition from weak to strong correlation. Significant correlation patterns are observed across different time scales. At short-term frequencies (4-16 days), intermittent strong correlations are evident, particularly at the beginning of 2015, mid-2018, and the end of 2022. Medium-term frequencies (16-64 days) show sustained moderate correlations, especially from mid-2016 to early 2017 and from mid-2018 to early 2019. Long-term frequencies (64-256 days) reveal several significant strong correlation zones, most notably from late 2015 to early 2016, from mid-2018 to early 2019, and from late 2020 to mid-2021. Notably, at ultra-long-term frequencies (>256 days), a continuous moderate correlation band is observed throughout the entire observation period, indicating a long-term foundational relationship between climate transition risk and European tourism stocks. Overall, this multiscale correlation pattern reflects the complex impact of climate transition risk on the European tourism sector, demonstrating varying degrees of association across different time scales and highlighting the ongoing and evolving influence of climate change on the industry (Lu and Zeng, 2023).

Next, we examine the dynamic connection between the TRI and the travel and leisure sector of the U.S. stock market (US) from 2015 to 2022. The color gradient from blue to red signifies a shift from weak to strong correlation. Significant correlation patterns across various time and frequency scales are observed. At short-term frequencies (4-16 days), there are frequent but intermittent strong correlations, particularly evident at the beginning of 2015, mid-2016, and the end of 2021. Medium-term frequencies (16-64 days) show more dispersed moderate correlations, especially in early 2016 and from mid- to late 2021. Long-term frequencies (64-256 days) exhibit a very significant strong correlation zone concentrated from 2019 to 2021, likely related to the enormous influence of the COVID-19 pandemic on the tourism sector. Notably, at ultra-long-term frequencies (>256 days), a continuous moderate correlation band is seen throughout the observation period, with a particularly strong correlation area from mid-2018 to the end of 2019. Overall, this multiscale correlation pattern reflects the complex impact of climate transition risk on the U.S. tourism sector, showing varying degrees of association across different time scales and underscoring the ongoing and changing influence of climate change, particularly in the long- and ultra-long-term contexts (Wu and Li, 2024).

Finally, we analyze the dynamic connection between the TRI and the travel and leisure sector of the UK stock market (UK) from 2015 to 2022. The complex correlation patterns across different time and frequency scales are evident. At short-term frequencies (4-16 days), frequent and significant strong correlations are observed, particularly at the beginning of 2015, mid-2016, early 2018, and the end of 2022. Medium-term frequencies (16-64 days) show several notable strong correlation zones, especially in early 2016, mid-2018, and from early to mid-2020. Long-term frequencies (64-256 days) reveal several significant strong correlation areas, with the most prominent being in early 2016, mid-2018 to early 2019, and early to mid-2020. Notably, at ultra-long-term frequencies (>256 days), a continuous moderate correlation band is present throughout the observation period, with a particularly strong correlation zone from mid-2019 to early 2020. Overall, this multiscale correlation pattern reflects the profound impact of climate transition risk on the UK tourism sector, showing significant and evolving associations through different time scales (Sun *et al*., 2024), especially in the medium to long term, highlighting the ongoing and complex influence of climate change on the UK tourism industry, potentially closely tied to specific climate policies and trends in tourism development.

## 5. Conclusions

This study employed quantile Granger causality assessment and wavelet coherence analysis to investigate the dynamic nexus betwixt climate risk and the performance of tourism equities in prominent European and US markets. Our investigation concentrated on two pivotal climate risk indicators: the PRI and the TRI. The results unveiled a multifaceted nonlinear relationship betwixt climate risk and the tourism industry, exhibiting substantial variations under distinct market conditions and temporal scales, which were of paramount importance for investors, policymakers, and the entire tourism sector.

The results of the quantile Granger causality analysis indicate a significant nonlinear relationship between climate risk indices and the tourism sectors of major European and American stock markets. Under extreme market conditions (i.e., when quantiles are close to 0 or 1), the impact of climate risk indices on the tourism sector is most pronounced. This may reflect an increased sensitivity of market participants to climate risks in extreme situations. Notably, near the median, the Granger causality is not significant, suggesting that under "normal" market conditions, climate risk factors may be overshadowed by other more direct economic factors. This phenomenon aligns with the "limited attention" theory in behavioral finance.

Wavelet coherence analysis further reveals the multiscale dynamic connection between climate risk and tourism stock performance. We find that both the PRI and the TRI exhibit multiscale characteristics in their impact on tourism stocks, showing significant correlations across short-term (4-16 days), medium-term (16-64 days), and long-term (>64 days) frequencies. This underscores the broad influence of climate factors on tourism performance. It is noteworthy that the impact patterns of PRI and TRI on tourism stocks differ significantly, indicating the need for detailed risk management strategies.

While all studied markets show sensitivity to climate risk, the correlation patterns differ significantly between countries, reflecting variations in geographical vulnerability, policy environments, and market structures. Additionally, the strength and direction of the correlations between climate risk and tourism stocks fluctuate over time, particularly observed during extreme market conditions or significant climate events.

These findings carry important implications for investors. Specifically, we recommend the following actionable strategies: (1) Develop dynamic risk assessment models that incorporate both physical and transition climate risks with different weights based on market conditions, using the quantile thresholds identified in our study as trigger points for portfolio rebalancing; (2) Implement a geographical diversification strategy focusing on markets with low climate risk correlation, particularly considering the 20-30% allocation to markets showing counter-cyclical climate risk patterns; and (3) Adopt a multi-horizon investment approach with separate strategies for different time scales.

For policymakers, the results of this study also have profound implications. We propose three key policy initiatives: (1) Establish a tiered climate risk response system with specific triggers and actions based on market conditions - including mandatory climate risk disclosure requirements for tourism companies when market volatility exceeds the 75th percentile, enhanced monitoring during extreme market conditions, and streamlined approval processes for climate adaptation projects; (2) Develop market-specific regulatory frameworks - for European markets, focus on strengthening cross-border climate risk coordination and standardizing reporting requirements; for American markets, emphasize state-level climate resilience programs and federal insurance mechanisms for extreme weather events; and (3) Create a transition support program including green finance initiatives with preferential rates for tourism companies investing in low-carbon technologies, tax incentives for early adopters of sustainable practices, and public-private partnerships for climate-resilient infrastructure development.

For tourism enterprises, our findings suggest several practical measures: (1) Implement a climate risk management system that monitors both physical and transition risks using our identified indicators, with quarterly assessments and annual strategy updates; (2) Develop climate adaptation plans with specific targets - 15-20% reduction in carbon intensity over 3 years, 30-40% increase in renewable energy use by 2027, and climate-proofing of at least 50% of physical assets against extreme weather events by 2028; and (3) Establish dedicated climate risk management teams with clear reporting lines to senior management and regular board oversight.

Overall, this study provides a direction for further exploration of the relationship between climate risk and the tourism sector. Future research could investigate the specific mechanisms behind the observed nonlinear relationships. Additionally, extending the research to firm-level data could provide deeper insights into how company-specific factors moderate the influence of climate risk on stock performance. Furthermore, integrating alternative climate risk measures, such as satellite-based physical risk assessments and regulatory compliance costs, could help address the current limitations in risk measurement. The development of more comprehensive climate risk metrics could potentially reveal stronger relationships than those identified in our study, particularly in the median quantiles where we currently observe weaker statistical significance. More specifically, future research paths could focus on three key areas. First, examining how digital transformation technologies (such as AI-driven climate risk prediction models, IoT-based real-time weather monitoring systems, and blockchain-enabled carbon tracking platforms) influence the tourism industry's resilience to climate risks.

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