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**Tail dependence in European stock markets amidst the Russo-Ukrainian war: Shifting linkages and their determinants**

Wojciech Grabowski[12] and Jakub Janus[3]

## Abstract

This study investigates the impact of the Russo-Ukrainian war on stock market connectedness in 24 European economies. Using a framework based on Clayton copulas, we identify changes in the left-tail dependence of stock market returns between the war and pre-war periods and explore their determinants through limited dependent variable models. We find that the war-induced shifts in the market connectedness are significant but not uniform, involving both elevated left-tail linkages (financial contagion) and instances of diminished connectedness and increased market resilience. Such diverse changes can be attributed not only to cross-country differences in stock market volatilities and trade dynamics but also to countries' proximity to the warzone and their reliance on fossil-fuel imports, particularly their pre-war energy dependence on Russia. Our results highlight the need to consider these vulnerabilities in portfolio diversification strategies of international investors, as well as in financial stability policies.

**Keywords:** stock markets; tail dependence; international market connectedness; financial contagion; Russia-Ukraine war

**JEL Classification:** E44, F36, G11, G15

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## 1. Introduction

As history shows, wars have disruptive effects on various aspects of economic activity, including production, trade, and finance. The Russian invasion of Ukraine on February 24, 2022, marks the beginning of a war-induced shock. Recent studies emphasize various international effects of the war, such as fluctuations in oil prices (Zhang et al., 2023), the rebalancing of fossil fuel sources away from Russia (Chepeliev, Hertel & van der Mensbrugghe, 2022), and disruptions in food supply chains (Tong, 2024). These effects are amplified by unprecedented sanctions imposed shortly after the military aggression, particularly by European economies (Almazán-Gómez et al., 2024). The invasion also significantly impacted financial markets, especially stock market returns, as documented in numerous studies. Globally, stock market indices incurred significant losses shortly after the invasion (Boungou & Yatié, 2022; Silva, Wilhelm, & Tabak, 2023). The responses were heterogeneous, with market returns in developed countries being more affected than in emerging ones (Boubaker et al., 2022) and differing from responses seen during the Global Financial Crisis or the Covid-19 pandemic (Izzeldin et al., 2023). However, much less is known about the effects of the war on changing dependencies across financial markets, with only a few studies addressing this issue (e.g., U, Lin, & Wang, 2024). Understanding these changes is crucial not only for comprehending the international transmission of shocks and financial contagion but also for identifying market-specific vulnerabilities. Consequently, investigating shifting patterns in stock market linkages can inform effective asset allocation and risk management strategies, as well as financial stability policy considerations.

This paper fills the existing gap by providing a comparative analysis of changes in linkages among European stock markets during the full-scale Russo-Ukrainian war. In the first part of the study, we employ an empirical approach based on Clayton copulas and bootstrap techniques to determine the dependence among stock markets over a two-year period following February 2022. We focus on the left-tail dependence in stock market returns and examine whether the transmission of extremely low returns between stock markets has changed since the outbreak of the war. The second part of the study uses a series of limited dependent variable models to explain the cross-sectional variation in the identified shifts in market interconnectedness. We investigate numerous potential determinants of these changes, including financial market performance, international trade linkages, macroeconomic factors, and political-economy considerations.

Our empirical results show that changes in European stock market tail dependence following the Russian invasion of Ukraine were significant but not uniform across countries. Importantly, these changes involve not only increases in left-tail connectedness (financial contagion) but also instances of diminished market interdependence and increased resilience. By examining the determinants of pairwise changes in market dependence, we demonstrate that larger shifts in the connectedness measures can be explained by relatively higher stock market volatilities, deterioration in international trade relations, proximity to the warzone, and pre-war reliance on energy imports, especially on fossil-fuel dependence on Russia. Our results suggest that these vulnerabilities should be considered in the assessment of portfolio diversification strategies, as well as financial stability and regulatory policies.

The contribution of this paper is threefold. First, we supplement the literature that investigates stock market returns in the aftermath of the Russo-Ukrainian war. Second, we compare left-tail dependence for European stock markets in the war and pre-war periods using data covering a full two years after the outbreak of the war, going beyond the narrow window following the Russian military aggression. Third, we identify the relative importance of several determinants of these changes, going beyond the standard channels, such as trade and macroeconomic vulnerabilities, and considering the specific nature of the crisis induced by the Russian invasion of Ukraine, such as the role of energy import dependence.

The remainder of the paper is structured as follows. The second section surveys the related literature. In the third section, we lay out the empirical strategy used in the study and describe the data. The results of the estimation of copulas and calculation of left-tail dependence measures, along with the cross-sectional evidence on the determinants of changes in stock market dependence, are presented in the fourth section. The fifth section concludes and outlines issues for further research.

## 2. Related literature

The paper primarily links to a growing literature devoted to the impact of Russian aggression of Ukraine on international financial markets. The first wave of studies in this area focuses on the immediate effects of the negative shock induced by the war on stock market indices. Based on a large sample of countries, Boungou & Yatié (2022) document a sizeable reaction of global equity markets to the outbreak of the war, which diminished several weeks after the invasion. Izzeldin et al. (2023), using Markov switching models on market volatilities, show that the reaction of stock markets in G7 economies to the war was indeed very quick but less intense than during the Covid-19 pandemic. However, Boubaker et al. (2022) show that the effects of the invasion on the abnormal returns of stock market indices displayed notable heterogeneities, mostly due to varying levels of economic globalization. Ahmed, Hasan, and Kamal (2023) confirm a considerable variation in the negative stock price reactions to the war in European countries, also highlighting differences among industries.

Several studies emphasize issues specific to the episode of Russian aggression in Ukraine, especially its impact on commodity markets and economies worldwide due to dependence on commodity prices. Deng et al. (2022) show that in the first weeks after the Russian invasion of Ukraine, stocks were more exposed to regulatory risks related to the possibility of transitioning to a low-carbon economy. Lo et al. (2022) find that negative pressure on stock market returns was amplified by dependence on commodity imports from Russia. Kumari, Kumar, & Pandey (2023) use an event study methodology to show that the diverse impact of the war on EU stock index returns may be partly explained by geographical location and differences in market efficiency. Based on firm-level data and a narrow window around the beginning of the invasion, Sun and Zhang (2023) demonstrate that the negative impact of the war was more significant for abnormal returns of firms located closer to Russia and with tighter trade linkages. Silva, Wilhelm, and Tabak (2023), employing a difference-in-difference design on a large panel of stock markets, identify proximity to the conflict as a major risk factor for European markets, while the trade channel appears more important for non-European markets.

Apart from analysing the performance of returns after the Russian invasion of Ukraine, fewer studies have focused on the impact of the war on financial asset volatilities and linkages between financial markets. Using a TVP-VAR methodology to measure return and volatility connectedness, Umar et al. (2022) demonstrate that interdependencies among financial assets substantially changed, giving rise to crisis-induced spillovers from European equity markets. Interestingly, they find that the invasion had a stronger impact on the longer-term connectedness of asset volatilities rather than returns. Focusing on European stock markets and using a frequency-domain spillover methodology, Ciocîrlan and Nițoi (2023) find increased but transitory spillover effects associated with the war, especially in Central and Eastern Europe. U, Lin, and Wang (2024), on the other hand, document a surge in volatility spillovers across stock and other markets starting in February 2022, largely attributed to long-term volatility stemming from war-related systemic risk.

## 3. Empirical methodology and data

Our empirical methodology relies on the copula approach which is used to capture nonlinear dependencies among time series. In general, estimating the marginal distributions and the copula function independently enables estimation of any multivariate distribution. While the correlation coefficient is an exhaustive measure of linear dependence for regular variables, it fails to capture potential nonlinearities in such dependencies. In addition, the copula approach is appropriate not only to measure the existence of financial contagion, understood as an event-related increase in market dependencies, but it also enables measuring the intensity of contagion. According to the Sklar's (1959) theorem, if $H$ is a distribution function of marginal functions $F_1, F_2, \dots, F_d$ if it exists, then a copula $C$ is defined as follows:

$$\underset{x \in R^d}{\forall} H(x_1, \dots, x_d) = C\big(F_1(x_1), \dots, F_d(x_d)\big). \tag{1}$$

When copulas are used, the dependence structure between markets is characterized by measures such as the Spearman's ρ or the Kendall's τ. In the case of two-dimensional variables $X$ and $Y$, the formulas defining τ and ρ are as follows:

$$\tau_C(X,Y) = 1 - 4 \int_{I^2} \frac{\partial C(u,v)}{\partial u} \frac{\partial C(u,v)}{\partial v} dudv, \tag{2a}$$

$$\rho_C(X,Y) = 12 \int_{I^2} (C(u,v) - uv) dudv. \tag{2b}$$

In what follows, we rely on the Kendall's τ, which has more intuitive interpretation, to evaluate the global dependence structure and develop contagion tests.

The focus of this study is on the European stock markets, due to the fact that those countries have been most directly affected by the war, not only through financial and economic links to Ukraine and Russia, but also through their multifaceted involvement in war, including the military equipment delivery, the influx of refugees, and the imposition of sanctions. The study covers the main stock markets in 24 European countries, summarized in Table 1, and the period between 2018-01-01 to 2024-02-24. Hence, it covers the period roughly four years before the full-scale Russian invasion on Ukraine and two years after. The log rates of returns are calculated in daily frequency, using the data sourced from Refinitiv Datastream.

[Table 1 around here]

Having prepared the underlying series, we apply the following four-step methodology to determine changes in the stock market dependencies across the European stock markets, similarly to the Benkraiem et al. (2022) study on the shifts in intermarket linkages following the Covid-19 pandemic.

*Step 1.* Parameters of the ARMA-GJR-GARCH models are estimated on the logarithmic rates of return of stock market indices in each economy. After the estimation of the parameters of the ARMA-GJR-GARCH models' heteroscedasticity and autocorrelation of stock market returns is removed. Standardized residuals are recovered.

*Step 2*. The sample is divided into two subperiod: before the start of the Russian invasion of Ukraine (2018-01-01 to 2022-02-23) and after the invasion began (2022-02-24 to 2024-02-24). The filtered returns are transformed into uniforms for both subperiods and the Kendall's τ measures are calculated.

*Step 3.* Different copulas are estimated by canonical maximum likelihood methods and the Akaike information criterion is used to select the most adequate copula[4].

*Step 4.* The bootstrap technique is used to calculate the variance-covariance matrix of parameters of copula, Kendall's $\tau$ measure and left-tail dependence measure (Trivedi & Zimmer, 2005).

Once the dependency measures are recovered, we explore their changes between the war and pre-war subperiods. The first possibility is a significant increase in cross-market linkages following a shock to one country or a group of countries, i.e. financial contagion (Forbes & Rigobon, 2012). contagion occurred after the outbreak of the Russian invasion of Ukraine is based on testing the following hypotheses:

$$H_0: \lambda_{war}^L - \lambda_{before}^L \leq 0, \tag{3a}$$

$$H_1: \lambda_{war}^L - \lambda_{before}^L > 0. \tag{3b}$$

After testing the hypotheses at the 0.05 significance level, we can construct a variable that captures the intensity of financial contagion (once it occurs) for all pairs $(A, B)$ of countries:

$$contagion^{A,B} = \begin{cases} \hat{\lambda}_{war}^L - \hat{\lambda}_{before}^L & if \quad H_0 \ is\ rejected, \\ 0 & otherwise. \end{cases} \tag{4}$$

[4] Such procedure is standard, if we analyse dependence for one pair of markets. However, in our case we are interested in the analysis of left-tail dependence. Therefore, copulas which enable calculation of the left-tail dependence measure are considered. Moreover, we compare left-tail dependence among different pairs. Therefore, the same copula is applied for all pairs. It turns out, that the Clayton copula outperforms other copulas in most cases. Therefore, in all cases the Clayton copula is estimated.

These variable captures heightened interconnectedness in the downturns of the markets and becomes our main object of interest.

However, we also consider another possibility, namely a significant decrease in the interdependencies of stock market returns, which can be understood as market decoupling and insulation, a weaking of cross-market tail connectedness. To construct this variable, we simply reverse the signs of the hypotheses testing in Equations (3a) and (3b), and define it as the absolute values of negative changes in tail connectedness.

In a similar fashion, and to provide sensitivity checks on the first two definition, we introduce three additional specifications of the pairwise market connectedness measure. First, we simplify the contagion definition and construct a binary variable that takes the value of one (instead of continuous values) when there is contagion identified between two markets, and zero otherwise. Second, we define an analogous binary variable for the negative changes in tail dependence. Third, we construct an ordinal, three-level variable that encompasses all three possibilities of changes in the tail dependence, namely the negative, zero, and positive values.

Once we construct all five variables that describe the changes in interconnectedness, we move to the next step of our empirical methodology. This step involves investigating the possible drivers of changes in the left-tail dependencies of the European equity markets between the war and pre-war subperiods. We estimate cross-sectional regressions in a pairwise (dyadic) setup, examining changes in the bidirectional dependence between all the stock markets in the sample. We consider a set of nine explanatory variables, summarized in Table 2.

[Table 2 around here]

There are two general approaches to constructing the explanatory variables. The first approach concerns financial and economic variables that adjust quickly, for which we take into account both war and pre-war values. Building on previous work in the field, notably Luchtenberg and Vu (2015), we define these variables as wartime vs. pre-war changes in the absolute difference. The most typical example is the first variable among the determinants, which shows differences in the relative volatility of stock market indices:

$$market\_volatility^{A,B} = |rv_{war}^{A} - rv_{war}^{B}| - |rv_{before}^{A} - rv_{before}^{B}|, \qquad (5)$$

where $rv_{war}$ is the mean value of the annualized realized variance, calculated using squared daily returns of stock market indices over the two-year period following the breakout of the war, while $rv_{before}$ is the corresponding value calculated for the period of 2018-01-01 to 2022-

02-24. As an increased market volatility is a marker of elevated idiosyncratic risk premium in a given market, we expect to find a positive relationship between $market\_volatility$ and positive changes in tail connectedness (financial contagion). Similarly to this variable, we construct the $gdp\_growth$ and $inflation\_rate$ variables, which shows changes in the average absolute differences in the GDP growth rates and inflation rates, respectively. In both cases, we anticipate an increase in these determinants to be positively related to shifts in cross-market dependence. Trade is measured as the difference between the post-war and pre-war share of bilateral trade in the total trade of countries. We expect a negative coefficient estimate on $trade\_bilateral$ due to a propagation of shocks that deteriorate the bilateral trade relationship to the stock market connectedness.

The second approach involves more slow-moving variables, using the pairwise sums of their average pre-war values. Given the pronounced role of energy after the breakout of the Russo-Ukrainian war, the first of these variables is defined as:

$$fuel\_net\_imp^{A,B} = 0.5 \times (fuel\_net\_imp^{A} + fuel\_net\_imp^{B}), \tag{6}$$

where subscripts A and B denote two countries in a pair. This variable is the average share of imports and exports of fuels in total imports and exports based on World Bank WDI data for the period 2018-2021. We expect higher values of this variable to be related to stronger contagion effects, particularly between two countries with high energy dependence. More directly related to the Russian aggression on Ukraine is the reliance on Russian fossil fuels (oil, coal, and natural gas), the variable we dub $energy\_dep\_ru$, provided by the International Energy Agency. Additionally, two variables capture the proximity to the war, which we expect to affect the probability of a country pair experiencing higher contagion effects. For the distance to Ukraine, $distance\_to\_ua$, we use the population-weighted harmonic mean distance between the most populated cities of each country. We also include an indicator variable for whether at least one country is contiguous to Ukraine or Russia, $contig\_ua\_ru$. Both geographical variables come from the CEPII Gravity database (Conte, Cotterelaz, & Mayer, 2022).

Given the nature of the dependent variable, which is highly concentrated at zero, we keep the pairwise regression as parsimonious as possible while accounting for the most important potential drivers of changes in tail connectedness in the post-war period. Using the set of determinants, we estimate a series of limited dependent variable models corresponding to the properties of the five specifications of the dependent variable described above. In the baseline specification, we employ the Tobit model to handle the variable with continuous positive values.

Second, we use logit and probit models for a simplified definition of contagion. Third, we examine negative (in absolute values) changes in tail dependence identified in the first stage of the analysis. Finally, we employ ordered logit and probit models when the dependent variable captures positive and negative changes in tail dependence. In all models, we introduce two-way clustered standard errors, with clusters at both nodes of a country pair to control for potential error correlations across pairs formed vis-à-vis a common country, making the inference more robust and preventing the overestimation of the effects of the potential determinants.

## 4. Empirical results and discussion

The first step of the empirical analysis involves the estimation of univariate ARMA($i$, $j$)-GJR-GARCH($q$, $p$) models, which serve as the basis for the calculation of the left-tail dependence measures. Table 3 presents the results of the model selection for each of the 24 European equity market returns, estimated for the entire period of the analysis. In most cases, the selected models involve ARMA orders of (1, 1) or (2, 2), while all except one return series are modelled using the (1, 1) GARCH order. The majority of stock market returns exhibit the asymmetric impact of shocks (the GJR component), with skewed GED and skewed T distributions of the residuals being equally numerous across the selected specifications.

[Table 3 around here]

Next, we proceed with the estimation of bivariate Clayton copulas for all pairs of stock market returns and calculate the Kendall τ dependence measures for the pre-war and post-war subperiods. Tables A1 and A2 in the Online Appendix show detailed values of the left-tail dependence coefficients, along with their statistical significance. Results of the copula estimation indicate that left-tail dependence between stock market returns was statistically significant for almost all pairs of indices in both subperiods. The matrix in Table 4 displays our main objects of interest, the differences in left-tail dependence measures between the two subperiods, which include 276 unique pairwise changes in the Kendall τ correlations among the 24 stock market indices.

[Table 4 around here]

The correlation matrix reveals 107 (around 38%) non-zero cases, with 44 (around 16%) positive changes and 63 (around 22%) negative changes in pairwise dependencies. This indicates that instances of financial contagion are present but quite heterogenous across countries. However, the average value of positive changes, 0.128, is higher in absolute terms than the average negative change, -0.108. To further illustrate these results, the left-hand side of Figure 1 displays a geographical analysis of cross-country differences in mean values of the pre- and post-war left-tail dependence, along with the distribution of the values from Table 4. The most positive average values are found in Lithuania, Finland, and Estonia, while the most negative values appear in Norway, Sweden, and Hungary. Only pairs involving the Latvian stock market show statistically significant left-tail dependence.

[Figure 1 around here]

By construction, the resulting distribution of changes in left-tail dependencies is inflated at zero, as shown in the right-hand side of Figure 1. Hence, the shifts in market connectedness are quite heterogeneous. The average value of country-level changes is close to zero, -0.004, with a standard deviation of 0.040. Moreover, Figure A1 in the Online Appendix compares the number of positive and negative changes in pairwise left-tail dependencies for each economy. Similarly, Lithuania and Finland exhibit the highest number of positive changes, while Norway and Sweden show the highest number of negative changes.

Having demonstrated the extent of these changes, we now investigate the underlying reasons for why some markets experience more pronounced shifts in tail dependence than others. Table 5 presents our baseline results, explaining changes in left-tail dependence using Tobit models.

[Table 5 around here]

The relative change in market volatility, a proxy for country-specific risk, is large, positive, and highly significant across all specifications. This finding suggests that an increased market risk premium is strongly associated with elevated stock market contagion. The consistent significance of this variable across all columns underscores its importance as a primary driver of contagion. In Column (2), the effects of macroeconomic factors such as GDP growth appear generally weak. However, the inflation rate shows some significance, indicating that higher inflation can contribute to increased financial contagion, possibly due to the economic instability it signals. The role of bilateral trade is highlighted by the negative coefficient estimate, which indicates that reductions in trade intensity during wartime are associated with a higher likelihood of contagion. This result points to the critical role of economic interdependencies in exacerbating market vulnerabilities during periods of geopolitical stress.

An important finding in Table 5 is the significant role of energy-related variables. Country pairs with stock markets in countries more reliant on fuel imports show higher susceptibility to contagion. This effect is particularly pronounced when considering energy dependence from Russia. When this specific measure is introduced, the effect diminishes, suggesting that direct reliance on Russian energy sources plays a critical role in this context. The robustness of this result, even when controlling for other determinants in Column (7), underscores the importance of energy dependencies in understanding market dynamics. Geographic proximity is another significant factor. Column (6) illustrates that countries sharing a border with Ukraine or Russia experience higher levels of contagion. This geographic factor likely reflects both direct economic ties and broader geopolitical risks that are more immediate for neighboring countries.

Moving to Table 6, the results based on alternative definitions of the dependent variable further support our baseline findings. Overall, the alternative specifications confirm many baseline findings but also highlight some nuanced differences. Columns (1) and (2) present the results of logit and probit regressions with a binary dependent variable. These results reaffirm the strong, positive relationship between market volatility and energy reliance on Russia. Bilateral trade linkages and changes in inflation rates also emerge as significant factors, complementing our baseline findings.

[Table 6 around here]

Columns (3) through (5) shift the focus to negative tail dependence. The effects here are generally weaker, as indicated by lower pseudo-$R^2$ values. Nevertheless, geographic proximity and energy dependence remain important factors in at least two of the three specifications. The reversal in the signs of most coefficients in these models, compared to the baseline case, reveals an interesting asymmetry between positive and negative changes in tail dependence. Notably, the lack of a significant effect of market volatility in these models, despite the expected negative sign in logit and probit specifications, contrasts with its consistent significance in contagion models, highlighting this asymmetry.

Finally, Columns (6) and (7) of Table 6 display the ordered logit and probit models, estimated using an ordinal dependent variable. The results are highly consistent with the baseline findings, demonstrating the robustness of our conclusions across different model specifications.

Overall, our results suggest that changes in stock market connectedness in Europe were substantial and extended well beyond the short-term effects of the Russian invasion of Ukraine in February 2022, as well as the narrow event windows around the war's outbreak. This finding supports Kumari, Kumar, and Pandey's (2023) conclusion that cross-market linkages of European stock markets significantly evolved during the war. Our findings also highlight the crucial role of energy dependency and trade linkages in driving shifts in market connectedness. Amidst the energy crisis induced by the war, investors' sentiment was predominantly influenced by the economies' reliance on imports of oil, coal, and natural gas. Economic interdependencies are propagated not only through trade but also through energy supply chains, underscoring the importance of energy diversification. Moreover, the critical nature of energy supplies and geopolitical tensions overshadowed other potential drivers of contagion, such as macroeconomic fundamentals. Although not directly, this finding corroborates the results of Boubaker et al. (2022) and Lo et al. (2022), using a different methodology that focuses on market tail dependencies. Finally, our analysis demonstrates that proximity to the conflict zone is a critical factor influencing stock market connectedness, adding to previous studies by Boungou and Yatié (2022) and Sun and Zhang (2023), which make this point concerning the market returns following the outbreak of the war.

## 5. Conclusion

What do we know about the impact of the Russian invasion of Ukraine on European stock market connectedness more than two years since the breakout of the war? This paper addresses this question through an empirical analysis of 24 European stock markets. Unlike most studies, we take a longer perspective, assessing the changes over the two years following the invasion in February 2022. In the first step, we employ Clayton copulas to examine changes in left-tail dependence. The second step of the analysis involves investigating the determinants of these changes using a series of limited dependent variable models, including Tobit and logit regressions, in a pairwise setting.

Our results show that the outbreak of the war brought significant changes, even in the longer term. However, these changes substantially differ across countries. We demonstrate that the differences can be ascribed to several vulnerabilities: relative increases in market volatility, breakdowns in international trade linkages, proximity to the warzone, and countries' reliance on energy imports, particularly fossil fuels from Russia. Given the energy crisis induced by the war, our findings have important implications for policymakers responsible for financial stability and international investors seeking to diversify portfolios. Beyond the immediate context, our study provides insights into the nature of financial contagion and resilience, contributing to a deeper understanding of how major geopolitical events can reshape financial markets.

A major limitation of this study is its focus on European markets, which have the most direct contact with the warzone and are the most affected by the war. Future studies may examine the determinants of pre-war vs. post-war differences in the tail dependence of stock markets in other regions, especially Asian markets, which have been affected differently. Another promising area of research is to investigate the changing drivers of contagion and flight to quality in other segments of financial markets, especially sovereign bond markets, and to compare these with the results obtained in this paper. Finally, given the importance of international energy dependence uncovered in this paper, it is advisable to further investigate the growing role of geopolitical risks, sanctions imposed on international trade, and the ongoing energy transformation for the cross-border linkages of equity markets.

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**Conflict of interest**

The authors declare no conflicts of interest related to this study.

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# Tables

**Table 1. Countries and stock market indices covered in the paper**

| Country code | Index name | Country code | Index name | Country code | Index name |
|---|---|---|---|---|---|
| AT | ATX | ES | IBEX | LV | OMX RIGA |
| BE | BEL20 | FI | HEX | LT | OMX VILNIUS |
| BG | SOFIX | FR | CAC40 | NL | AEX |
| CH | SMI | GB | FTSE250 | NO | OSEAX |
| CZ | PX | GR | ATHEX | PL | WIG |
| DE | DAX | HU | BUX | PT | PSI20 |
| DK | OMX COPENHAGEN | IE | ISEQ | RO | BET |
| EE | OMX TALLIN | IT | FTSE MIB | SE | OMX STOCKHOLM |

*Notes:* The table lists the ISO country codes, and respective names of the main stock markets indices used to calculate the log rates of return employed in the study.

**Table 2. Potential determinants of shifts in left-tail dependence of stock market returns: description and data sources**

| Mnemonic | Description | Raw data source |
|---|---|---|
| $market\_volatility$ | Change between the post-war (2022-2024) and pre-war (2018-2021) absolute differences of the annualized realized variance of stock market index returns in a pair of countries. | Refinitiv Datastream |
| $gdp\_growth$ | Change in the post-war and pre-war average absolute differences in the annual real GDP log growth rates between two countries. | IMF International Financial Statistic |
| $inflation\_rate$ | Change in the post-war and pre-war average absolute differences in the monthly year-over-year CPI inflation rates between two countries. | IMF International Financial Statistic |
| $trade\_bilateral$ | Difference of the post-war and pre-war share of the bilateral trade of a pair of countries in the total trade of these countries with the rest of the World. | IMF Directions of Trade |
| $fuel\_net\_imp$ | Pairwise sum of the difference in each country's share of imports of fuels and exports of fuels in total imports and exports in the pre-war period (2018-2021). | WB World Development Indicators |
| $energy\_dep\_ru$ | Pairwise sum of the share of total imports of energy commodities – oil, coal, and natural gas – from Russia in the domestic fuel consumption in the pre-war period. | International Energy Agency |
| $distance\_to\_ua$ | Pairwise sum of log population-weighted average distance (in kilometres) between the most populated cities of each country and Ukraine. | CEPII Gravity |
| $contig\_ua\_ru$ | Indicator variables; takes the value of one when at least one country in a pair (excluding the Norway-Russia border in the Arctics) shares border with Ukraine or Russia, and zero otherwise. | CEPII Gravity |

*Notes:* The table summarizes the set of potential determinants of changes in investigated in the study and corresponding raw data sources.

**Table 3. The results of model selection for the univariate modelling of log returns in the European stock markets**

| Country code | ARMA order | GARCH order | Asymmetric impact of shocks | Distribution of innovation |
|---|---|---|---|---|
| AT | (1,1) | (1,1) | Yes | Skewed GED |
| BE | (2,2) | (1,1) | Yes | Skewed T |
| BG | (2,2) | (1,1) | No | Skewed GED |
| CH | (2,2) | (1,1) | Yes | Skewed T |
| CZ | (2,2) | (1,1) | Yes | Skewed GED |
| DE | (2,2) | (1,1) | Yes | Skewed T |
| DK | (2,2) | (1,2) | Yes | Skewed T |
| EE | (2,2) | (1,1) | No | Skewed GED |
| ES | (2,2) | (1,1) | Yes | Skewed T |
| FI | (0,0) | (1,1) | Yes | Skewed T |
| FR | (2,2) | (1,1) | Yes | Skewed GED |
| GB | (2,2) | (1,1) | Yes | Skewed T |
| GR | (2,2) | (1,1) | Yes | Skewed GED |
| HU | (1,1) | (1,1) | Yes | Skewed T |
| IE | (0,0) | (1,1) | No | Skewed T |
| IT | (2,2) | (1,1) | Yes | Skewed T |
| LV | (2,2) | (1,1) | Yes | Skewed GED |
| LT | (1,1) | (1,1) | Yes | Skewed GED |
| NL | (1,1) | (1,1) | Yes | Skewed T |
| NO | (1,1) | (1,1) | Yes | Skewed GED |
| PL | (1,1) | (1,1) | Yes | Skewed GED |
| PT | (2,2) | (1,1) | Yes | Skewed T |
| RO | (2,2) | (1,1) | Yes | Skewed GED |
| SE | (1,1) | (1,1) | No | Skewed GED |

*Notes:* The table shows the details of the ARMA-GJR-GARCH model specifications selected for each country using the Akaike information criterion. The estimation is based on the logarithmic rates of daily stock market returns between 2018-01-01 and 2024-02-24.

**Table 4. Differences between left-tail dependence between the war and pre-war subperiods**

| | AT | BE | BG | CH | CZ | DE | DK | EE | ES | FI | FR | GB | GR | HU | IE | IT | LT | LV | NL | NO | PL | PT | RO | SE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AT | - | 0 | 0 | 0 | -0.04 | 0.08 | 0.01 | 0.09 | 0.10 | 0.16 | 0 | 0 | 0 | 0 | 0 | 0 | 0.21 | 0 | 0.13 | -0.14 | 0 | 0 | 0 | -0.19 |
| BE | 0 | - | 0 | 0.07 | 0 | 0 | 0 | 0 | -0.04 | 0 | -0.06 | 0 | 0 | -0.09 | 0 | 0 | 0.24 | 0 | -0.04 | -0.09 | 0 | -0.08 | 0 | -0.16 |
| BG | 0 | 0 | - | -0.01 | 0 | 0 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.05 | 0 | 0 | 0 | 0 |
| CH | 0 | 0.07 | -0.01 | - | 0 | 0 | -0.10 | 0 | 0 | 0 | 0 | 0.10 | 0 | -0.15 | 0 | 0 | 0.30 | 0 | -0.03 | -0.18 | 0 | 0 | 0 | -0.17 |
| CZ | -0.04 | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0.08 | 0 | 0 | 0 | -0.08 | 0 | 0 | 0 | 0 | 0 | -0.27 | -0.17 | -0.09 | 0 | -0.12 |
| DE | 0.08 | 0 | 0 | 0 | 0 | - | -0.12 | 0 | 0 | 0 | 0 | 0.13 | 0 | 0 | -0.08 | -0.10 | 0.26 | 0 | 0 | -0.08 | 0.07 | -0.06 | 0 | 0.16 |
| DK | 0.01 | 0 | 0 | -0.10 | 0 | -0.12 | - | 0 | 0 | 0 | -0.09 | 0.01 | 0 | 0 | -0.12 | -0.13 | 0 | 0 | -0.12 | 0 | 0 | -0.11 | 0 | 0 |
| EE | 0.09 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 0.01 | 0 | 0 | 0 | 0 | -0.06 | -0.06 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.14 |
| ES | 0.10 | -0.04 | 0.02 | 0 | 0 | 0 | 0 | 0 | - | 0.16 | 0 | 0 | 0 | 0 | 0 | 0 | 0.25 | 0 | 0 | 0 | 0.05 | 0 | 0 | -0.09 |
| FI | 0.16 | 0 | 0 | 0 | 0.08 | 0 | 0 | 0.01 | 0.16 | - | 0 | 0.14 | 0 | 0.10 | 0 | 0 | 0.32 | 0 | 0 | 0 | 0.15 | 0.12 | 0 | -0.11 |
| FR | 0 | -0.06 | 0 | 0 | 0 | 0 | -0.09 | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0 | 0.23 | 0 | 0 | 0 | 0.07 | -0.10 | 0 | -0.12 |
| GB | 0 | 0 | 0 | 0.10 | 0 | 0.13 | 0.01 | 0 | 0 | 0.14 | 0 | - | 0 | -0.11 | 0 | 0 | 0.26 | 0 | 0 | -0.17 | 0.13 | 0 | 0 | -0.23 |
| GR | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | -0.02 | 0.12 | 0 | 0 | -0.11 | 0 | 0 | -0.09 | 0 |
| HU | 0 | -0.09 | 0 | -0.15 | -0.08 | 0 | 0 | 0 | 0 | 0.10 | 0 | -0.11 | 0 | - | 0 | 0 | 0 | 0 | 0 | -0.23 | -0.18 | -0.08 | 0 | -0.14 |
| IE | 0 | 0 | 0 | 0 | 0 | -0.08 | -0.12 | -0.06 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IT | 0 | 0 | 0 | 0 | 0 | -0.10 | -0.13 | -0.06 | 0 | 0 | 0 | 0 | -0.02 | 0 | 0 | - | 0 | 0 | -0.10 | 0 | 0 | 0 | 0 | 0 |
| LT | 0.21 | 0.24 | 0 | 0.30 | 0 | 0.26 | 0 | 0 | 0.25 | 0.32 | 0.23 | 0.26 | 0.12 | 0 | 0 | 0 | - | 0 | 0.25 | 0 | 0.20 | 0.11 | 0 | 0 |
| LV | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0 | 0 |
| NL | 0.13 | -0.04 | 0 | -0.03 | 0 | 0 | -0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.10 | 0.25 | 0 | - | 0 | 0 | 0 | 0 | -0.11 |
| NO | -0.14 | -0.09 | -0.05 | -0.18 | -0.27 | -0.08 | 0 | 0 | 0 | 0 | 0 | -0.17 | -0.11 | -0.23 | 0 | 0 | 0 | 0 | 0 | - | -0.11 | 0 | -0.23 | -0.22 |
| PL | 0 | 0 | 0 | 0 | -0.17 | 0.07 | 0 | 0 | 0.05 | 0.15 | 0.07 | 0.13 | 0 | -0.18 | 0 | 0 | 0.20 | 0 | 0 | -0.11 | - | 0 | 0 | -0.07 |
| PT | 0 | -0.08 | 0 | 0 | -0.09 | -0.06 | -0.11 | 0 | 0 | 0.12 | -0.10 | 0 | 0 | -0.08 | 0 | 0 | 0.11 | 0 | 0 | 0 | 0 | - | 0 | -0.12 |
| RO | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.09 | 0 | 0 | 0 | 0 | 0 | 0 | -0.23 | 0 | 0 | - | 0 |
| SE | -0.19 | -0.16 | 0 | -0.17 | -0.12 | 0.16 | 0 | 0.14 | -0.09 | -0.11 | -0.12 | -0.23 | 0 | -0.14 | 0 | 0 | 0 | 0 | -0.11 | -0.22 | -0.07 | -0.12 | 0 | - |

*Notes:* The table displays a matrix of pairwise differences in Kendall tau correlation between the war (2022-02-24 to 2024-02-24) and pre-war (2018-01-01 to 2022-02-23) subperiods. The measures of dependencies are based on Clayton copulas and ARMA-GJR-GARCH models estimated using daily log returns of respective stock market indices. ISO country codes are provided in the first column and the first verse of the table. Zeroes at the intersection of two country codes denote a lack of a statistically significant left-tail dependence at the 0.05 significance level, with test statistics obtained using a bootstrap procedure. Positive values indicate a significant increase in left-tail dependence, while negative values show a significant decrease in left-tail dependence.

**Table 5. Determinants of positive changes in tail dependence (financial contagion) across the European stock markets between the war and pre-war subperiods in Tobit regressions**

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| $market\_volatility$ | 0.431*** | 0.363*** | 0.428*** | 0.456*** | 0.428*** | 0.360*** | 0.360*** |
| | (0.101) | (0.084) | (0.104) | (0.105) | (0.082) | (0.090) | (0.084) |
| $gdp\_growth$ | | 0.009 | | | | | 0.008 |
| | | (0.012) | | | | | (0.008) |
| $inflation\_rate$ | | 0.022* | | | | | 0.013 |
| | | (0.013) | | | | | (0.09) |
| $trade\_bilateral$ | | | -0.206** | | | | -0.260*** |
| | | | (0.091) | | | | (0.093) |
| $fuel\_net\_imp$ | | | | 1.464*** | 1.386 | | |
| | | | | (0.492) | (0.871) | | |
| $energy\_dep\_ru$ | | | | | 0.469*** | | 0.575*** |
| | | | | | (0.114) | | (0.152) |
| $distance\_to\_ua$ | | | | | | 0.039 | 0.097 |
| | | | | | | (0.053) | (0.066) |
| $contig\_ua\_ru$ | | | | | | 0.147** | 0.061* |
| | | | | | | (0.058) | (0.037) |
| $Intercept$ | -0.205*** | -0.264*** | -0.199*** | -0.247*** | -0.324*** | -0.312*** | -0.437*** |
| | (0.055) | (0.078) | (0.054) | (0.060) | (0.078) | (0.094) | (0.131) |
| Pseudo-$R^2$ | 0.050 | 0.115 | 0.075 | 0.118 | 0.277 | 0.123 | 0.364 |
| AIC | 142.2 | 136.9 | 140.7 | 134.5 | 113.8 | 135.8 | 109.2 |
| BIC | 153.1 | 155.0 | 155.1 | 149.0 | 131.9 | 153.9 | 141.8 |

*Notes:* The table shows the estimation results of the pairwise regression with the dependent variable defined as positive changes in the left-tail dependence among the European stock markets (i.e., financial contagion) between the war and pre-war subperiods using the Tobit model. Robust standard errors, two-way clustered at both countries in a country pair are given in brackets. Significance levels denoted as $p < 0.1$ *, $p < 0.05$ **, $p < 0.01$ ***. The McFadden pseudo-$R^2$, the Akaike information criterion, and the Bayes information criterion are given at the bottom of the table.

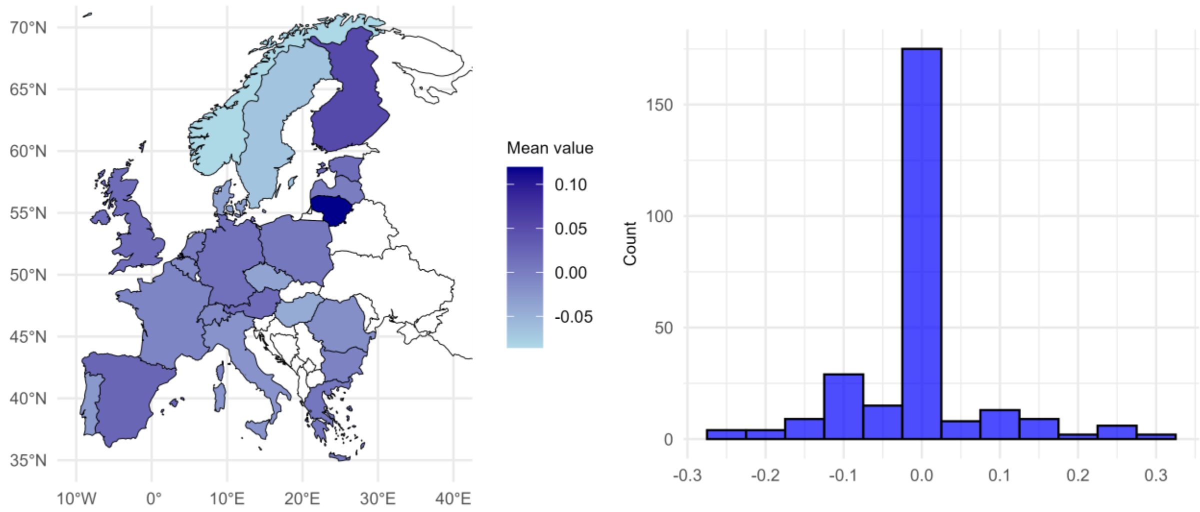
**Table 6. Determinants of changes in tail dependence across the European stock markets between the war and pre-war subperiods: alternative definitions of the dependent variables**

| Dep. variable: | Positive changes in tail dependence | | Negative changes in tail dependence | | | All changes in tail dependence | |
|---|---|---|---|---|---|---|---|
| Model: | Logit | Probit | Tobit | Logit | Probit | Ordered logit | Ordered probit |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| $market\_volatility$ | 3.806*** | 2.012*** | 0.001 | -0.153 | -0.078 | 0.666** | 0.424** |
| | (0.984) | (0.416) | (0.030) | (0.299) | (0.177) | (0.327) | (0.189) |
| $gdp\_growth$ | 0.113 | 0.057 | 0.008 | 0.119* | 0.066 | -0.038 | -0.019 |
| | (0.093) | (0.048) | (0.006) | (0.069) | (0.040) | (0.053) | (0.031) |
| $inflation\_rate$ | 0.124 | 0.075* | 0.006 | 0.077 | 0.044 | 0.013 | 0.007 |
| | (0.078) | (0.043) | (0.006) | (0.064) | (0.038) | (0.066) | (0.036) |
| $trade\_bilateral$ | -2.924* | -1.418 | 0.104* | 1.621** | 0.932** | -1.827** | -1.051** |
| | (1.722) | (1.015) | (0.055) | (0.732) | (0.435) | (0.851) | (0.499) |
| $energy\_dep\_ru$ | 5.053*** | 2.777*** | -0.250* | -2.359 | -1.378* | 3.487** | 1.996*** |
| | (1.591) | (0.896) | (0.138) | (1.512) | (0.802) | (1.139) | (0.703) |
| $distance\_to\_ua$ | 1.028 | 0.556 | -0.012 | 0.041 | 0.000 | 0.418 | 0.240 |
| | (0.687) | (0.379) | (0.035) | (0.396) | (0.228) | (0.429) | (0.251) |
| $contig\_ua\_ru$ | 0.732 | 0.360 | -0.098** | -1.216** | -0.690** | 1.051*** | 0.569*** |
| | (0.479) | (0.273) | (0.044) | (0.507) | (0.292) | (0.351) | (0.200) |
| $Intercept$ | -4.431*** | -2.471*** | -0.025 | -0.506 | -0.294 | 0.213 | 0.076 |
| | (1.357) | (0.733) | (0.065) | (0.697) | (0.398) | (0.701) | (0.422) |
| $Intercept\ (2)$ | | | | | | 3.476*** | 1.993*** |
| | | | | | | (0.826) | (0.475) |
| Pseudo-$R^2$ | 0.160 | 0.156 | 0.186 | 0.093 | 0.092 | 0.083 | 0.082 |
| AIC | 219.3 | 220.4 | 123.5 | 284.8 | 285.1 | 489.0 | 489.6 |
| BIC | 248.2 | 249.3 | 156.0 | 313.7 | 314.1 | 521.5 | 522.1 |

*Notes:* The table shows the estimation results of the pairwise regression using the alternative definitions of changes in the left-tail dependence across the European stock markets between the war and pre-war subperiods. Columns (1) and (2) display estimates based on the binary dependent variables showing positive changes in tail dependence. Column (3) shows estimates based on the absolute values of negative changes in tail dependence, while columns (4)-(5) use a corresponding binary dependent variable. Columns (6)-(7) display estimates based on the ordinal variable that captures both positive and negative differences in tail dependence. Robust standard errors, two-way clustered at both countries in a country pair are given in brackets. Significance levels denoted as p < 0.1 *, p < 0.05 **, p < 0.01 ***. The McFadden pseudo-$R^2$, the Akaike information criterion, and the Bayes information criterion are given at the bottom of the table.

# Figures

**Figure 1. Average values of the changes of the left-tail dependence between the war and pre-war subperiods across the European stock market returns (LHS) and their total empirical distribution (RHS)**




*Notes:* The LHS of the figure displays a map of average changes in left-tail dependence of a stock market returns between the war and pre-war subperiods in a given country vis-à-vis the rest of the stock markets in the sample obtained using the estimated ARMA-GJR-GARCH models, Clayton copulas, and Kendall tau correlations. The RHS of the figure shows the histogram of all the positive, negative, and not significant (zero) changes in the estimated cross-market dependencies. See also Table 4.