

Market Risk Modeling and Stress Testing: Volatility Spillover, Asymmetric Leverage Effect and Two-Stage GARCH-DID Empirical Framework

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Abstract:

Against the backdrop of deepening global financial integration, cross-border liquidity shifts trigger volatility swings and asymmetric tail risks in China's A-share and Hong Kong markets. Traditional single-stage GARCH models fail to identify causal policy spillovers, while static stress testing cannot capture time-varying risk structures. This paper constructs a two-stage GARCH-DID quasi-natural experiment framework, embedding DID interactions into the EGARCH conditional variance equation, and develops a fully reproducible RStudio rolling-window dynamic stress testing pipeline. Taking the 2020 Fed unlimited QE as a single-period exogenous shock, this study adopts a PSM-DID design with high-foreign-ownership firms as the treatment group. To isolate monetary spillovers from pandemic interference, it employs event-study parallel tests, double-layer placebo randomization and lagged grouping variables. Results show loose global liquidity exerts volatility smoothing effects and mitigates asymmetric leverage risk from negative news. Dynamic rolling-window EGARCH stress testing outperforms static historical approaches in out-of-sample tail risk forecasting, passing Kupiec and Christoffersen backtesting. Robustness tests—including double-layer placebo trials, two-way clustered standard error correction and alternative rolling windows—consistently validate core conclusions. This paper provides a standardized open-source technical paradigm for cross-border market risk supervision under capital account liberalization.

Keywords: Global Liquidity Shocks; Two-Stage GARCH-DID; Asymmetric Leverage.

1. Introduction

1.1 Research Background

With deepening global financial integration and accelerated liberalization of cross-border capital flows, global equity markets exhibit prominent time-varying co-movement and cross-border risk contagion. Monetary policy adjustments and global liquidity shocks originated from major advanced economies transmit rapidly to emerging capital markets through three core channels: cross-border capital flows, cross-market asset repricing, and global investor sentiment spillover. Such exogenous policy shocks often lead to sharp volatility surges, amplify asymmetric downside tail risks, and ultimately generate imported systemic financial risks in China's onshore A-share market and offshore Hong Kong stock market.

Existing mainstream market risk monitoring tools have two fundamental flaws. First, static single-stage GARCH models only capture the inherent volatility clustering of asset returns and cannot separate the causal impacts of exogenous global liquidity policy shocks on time-varying stock volatility. These models merely identify correlations between liquidity and volatility, conflate correlation with causality, and fail to address endogeneity arising from reverse causality and omitted variables [1]. Second, traditional static historical stress testing adopts fixed historical extreme crisis scenarios as shock benchmarks, assumes invariant market risk structures, ignores the dynamic evolution of market risks and heterogeneous responses of different assets to external policy shocks, thereby systematically underestimating extreme tail risks and weakening risk early warning efficiency [2].

In contemporary financial econometrics, RStudio has become the dominant open-source software for volatility modeling and quasi-natural experiment evaluation, equipped with a full set of quantitative packages covering data cleaning, panel regression, GARCH estimation, propensity score matching and robust standard error adjustment. This integrated toolchain supports fully reproducible empirical procedures, including data preprocessing, volatility fitting, DID causal identification, multi-scenario stress simulation and multi-dimensional robustness tests. It offers standardized and replicable technical support for research on cross-border risk spillover causality and dynamic stress testing, filling the research gap of a unified open-source empirical paradigm in existing literature [3]. The Federal Reserve's quantitative easing expansion in March 2020 coincided with the outbreak of the global COVID-19 pandemic, resulting in mixed exogenous shocks. This paper introduces multi-layer causal identification tools, including event-study parallel trend tests, double-layer random placebo tests and lagged grouping design, to isolate the independent cross-border spillover

effects of monetary liquidity policies from pandemic interference [4].

1.2 Core Research Questions

Frequent adjustments to global liquidity policies and intensified cross-border financial risk contagion motivate this study to construct an innovative two-stage hybrid GARCH-DID empirical framework based on single-period exogenous policy quasi-natural experiments, addressing three understudied research puzzles:

Causal identification of volatility spillover: Different from VAR and DCC-GARCH models that only analyze correlations, this paper establishes a classic 2×2 DID design centered on the 2020 Fed liquidity easing shock, quantifies the net causal effects of overseas liquidity policies on time-varying volatility of A-shares and Hong Kong stocks, and distinguishes policy-driven volatility changes from endogenous market fluctuations [1].

Heterogeneous mitigation of asymmetric leverage risks: Examine whether global liquidity easing weakens asymmetric volatility triggered by negative market news, compare policy effects across firms with different foreign capital exposure, and embed triple interaction terms into asymmetric volatility models to quantify the marginal mitigation effects of policies on leverage risks [5].

Comparative forecasting performance of dynamic and static stress testing: Set multiple global crisis shock scenarios to compare the tail risk forecasting accuracy of static historical stress testing and rolling-window EGARCH dynamic stress testing; introduce Kupiec and Christoffersen regulatory backtesting indicators to verify the practical advantages of time-varying volatility models in extreme risk supervision [6].

1.3 Marginal Innovations

Compared with existing literature, this paper adopts a clear two-stage estimation logic to avoid causal confusion and proposes three progressive innovations in methodology and research perspective:

Innovation 1: Causal Identification — Two-Stage GARCH-DID Framework with Block Bootstrap Correction

Following a strict sequential logic of purifying confounding return factors before estimating policy impacts on volatility, this paper organically integrates DID quasi-natural experiment design and EGARCH asymmetric volatility modeling [7].

Stage 1 adopts two-way fixed-effects panel regression to eliminate disturbances from corporate fundamentals and market sentiment, extracting residual returns free of endogenous interference. De-meaning via fixed effects alters residual volatility distributions and generates statistical bias in subsequent volatility estimation. This paper

employs time-series block bootstrap resampling to reconstruct the empirical distribution of coefficients and eliminate bias caused by two-stage sequential estimation [7].

Stage 2 directly embeds DID interaction terms into asymmetric volatility models to separate the differentiated impacts of policies on overall volatility and asymmetric leverage characteristics. All regression standard errors are corrected via 22-day continuous trading block bootstrap with 2,000 repeated iterations to eliminate statistical bias derived from residuals.

This two-stage design effectively mitigates reverse causality and omitted variable bias prevalent in single-stage volatility regressions, enabling rigorous causal identification of cross-border policy risk shocks [8].

Innovation 2: Research Dimension — Extending Spillover Analysis from Return Level to Asymmetric Tail Volatility Level

Most existing literature on global liquidity spillover only discusses policy impacts on average stock returns, ignoring time-varying volatility and asymmetric downside tail risk characteristics. This paper shifts the research perspective to conditional volatility and asymmetric leverage dimensions, improves the theoretical system of cross-border financial risk spillover, and fills the empirical gap regarding how external liquidity policies reshape market tail risk features [5].

Innovation 3: Empirical Toolchain — Standardized Fully Reproducible RStudio Operation System

This paper develops an annotated open-source full empirical workflow covering data cleaning, PSM matching, panel regression, rolling-window GARCH calibration, DID effect decomposition, multi-scenario stress simulation and multi-angle robustness tests. All core operational parameters are fully disclosed to improve transparency and replicability, forming a unified technical framework for dynamic market risk modeling applicable to regulators and financial institutions [9].

2. Literature Review and Research Hypotheses

2.1 Literature Review

2.1.1 Global financial cycle and cross-border volatility spillover

Classical studies confirm the US monetary policy-dominated global financial cycle, where cross-border liquidity changes act as core drivers of capital flows and asset price fluctuations in emerging markets. Mainstream empirical tools including VAR, BEKK-GARCH and DCC-GARCH are adopted to test cross-market volatility co-movement [1].

Nevertheless, correlation-based time series models cannot isolate exogenous liquidity policy shocks and fail to resolve endogeneity between market volatility and macro fundamentals. Research lacking quasi-natural experiment causal identification cannot accurately separate the pure causal effects of overseas liquidity policies, greatly reducing empirical credibility.

Recent literature published from 2023 to 2025 applies DCC-GARCH to test the spillover effects of US monetary policies on China's cross-border stock markets without DID causal identification [1]. Other studies focusing on emerging markets only analyze capital flow volatility under geopolitical risks without discussing asymmetric stock tail risks [2]. Few papers integrate DID identification into volatility models, which creates research space for the hybrid GARCH-DID framework constructed in this paper [8].

2.1.2 GARCH family volatility models and integrated GARCH-DID research

The baseline GARCH model and improved EGARCH model have become standard tools for depicting financial heteroskedasticity, and EGARCH effectively captures the leverage effect that negative news triggers larger volatility shocks [6].

A small number of papers attempt to combine DID and GARCH, yet two obvious defects remain: most adopt a separated two-step approach of calculating volatility first then conducting regression, without embedding policy interaction terms into variance equations to quantify marginal leverage effects; almost no literature uses bootstrap to correct statistical bias brought by first-stage residuals [7]. Recent domestic and overseas studies merely apply GARCH or DID independently without organic integration, and quantitative examinations of how liquidity policies restrain asymmetric market risks are scarce, leaving ample research room [8].

2.1.3 Market risk modeling and stress testing mechanisms

Stress testing serves as a core regulatory tool for measuring extreme loss exposure. Traditional static stress testing selects fixed historical crisis events as shock benchmarks and assumes constant market risk structures, which severely underestimates tail risks amid shifts in global liquidity cycles [6].

Cutting-edge research attempts to integrate dynamic GARCH with stress testing but has two deficiencies: empirical operation procedures are fragmented without unified open-source reproducible codes; performance evaluation only relies on mean absolute error (MAE) and root mean square error (RMSE) loss functions, lacking official regulatory backtesting indicators such as Kupiec and Christoffersen, which cannot fully verify the advantages

of dynamic volatility models [3, 6].

2.1.4 Conceptual distinction between PSM balance test and DID parallel trend test

Numerous empirical papers confuse the two testing tools, and this paper clarifies their core differences:

The PSM balance test is a preprocessing step prior to DID estimation. It only eliminates cross-sectional gaps in observable characteristics between the treatment and control groups and cannot verify counterfactual trends.

The parallel trend test is the core identification test of DID. It relies on event-study regressions to judge whether the treatment and control groups maintain consistent volatility trends before policy shocks, and must be conducted after completing PSM matching [4].

This paper strictly separates the two testing steps in empirical design. PSM only balances cross-sectional covariates and cannot guarantee consistent pre-policy time trends; thus an independent event-study parallel trend regression is added to estimate dynamic coefficients for 12 periods before and after policy shocks. Insignificant pre-policy coefficients satisfy the core counterfactual assumption of quasi-natural experiments [4].

2.2 Research Hypotheses

Combined with theoretical transmission mechanisms and gaps in existing literature, three testable hypotheses are proposed:

Hypothesis H1 (Volatility Smoothing Effect): Loose overseas liquidity policies significantly reduce the conditional volatility of China's A-shares and Hong Kong stocks. Sufficient global liquidity boosts capital inflows via Stock Connect channels, improves secondary market liquidity, raises investor risk appetite and stabilizes asset price fluctuations [1].

Hypothesis H2 (Asymmetric Leverage Mitigation Effect): Global liquidity easing significantly weakens volatility amplification triggered by negative news. Abundant cross-border capital buffers panic selling behaviors, narrows the gap in volatility responses to positive and negative news, and reduces leverage characteristics of downside tail risks [5].

Hypothesis H3 (Superiority of Dynamic Stress Testing): Rolling-window EGARCH dynamic stress testing outperforms static historical stress testing in tail risk forecasting. Dynamic models capture time-varying volatility and heterogeneous policy responses, pass full sets of regulatory backtesting standards, and generate more accurate measurements of Value-at-Risk (VaR) and Conditional Value-at-Risk (CVaR) [6].

3. Data and Variable Definition

3.1 Sample and Data Sources

This paper constructs daily firm-level panel data covering all industries of A-share and Hong Kong stock markets, with the sample period spanning 2018 to 2022. Taking the 2020 Fed quantitative easing shock as the core policy node, this dataset fully captures changes in volatility spillover before and after liquidity easing.

Data Sources

Daily firm trading data and financial indicators: China Stock Market & Accounting Research (CSMAR) Database;

Global macro liquidity and market sentiment indicators: Federal Reserve Economic Data (FRED) Database.

Data processing rules based on RStudio packages:

Eliminate ST stocks, delisted samples and observations with severe missing values;

Winsorize daily returns at the 1% and 99% quantiles to remove extreme abnormal noise;

Implement 1:3 nearest-neighbor PSM matching with a caliper threshold of 0.05, and construct balanced panel data for subsequent two-stage estimation after matching [4].

3.2 Core Variable Definitions

3.2.1 DID quasi-natural experiment variables

This paper constructs a single-period 2×2 DID model based on the Fed's unlimited QE in 2020 [4].

TREAT: Dummy variable for the treatment group. To address self-selection bias caused by grouping based on contemporaneous foreign shareholdings, the one-quarter lagged foreign ownership ratio is adopted for grouping. Firms with lagged foreign shareholdings ranking in the top 30% are defined as the treatment group with high cross-border capital dependence, while those in the bottom 30% form the control group. Three alternative grouping schemes are reserved for robustness checks: continuous foreign capital interaction terms, dynamic rolling grouping and lagged covariate matching [5].

POST: Time dummy variable, equal to 1 from March 2020 to December 2022 after QE implementation, and 0 from January 2018 to February 2020 in the pre-policy period. The event-study design estimates dynamic pre-policy trend coefficients to separate pandemic interference [4].

TREAT $\times$ POST: Baseline two-way DID interaction term, measuring the net causal impact of liquidity easing on stock volatility after eliminating self-selection and compound shock interference.

TREAT $\times$ POST $\times$ News: Triple interaction term. News equals 1 on trading days with negative aggregate market returns, used to test the heterogeneous mitigation effects

of policies on asymmetric leverage risks [5].

3.2.2 Two-stage dependent variables

Stage 1 Dependent Variable: Daily logarithmic stock returns calculated from closing prices, serving as raw inputs for volatility modeling.

Stage 2 Dependent Variable: Time-varying conditional volatility extracted from the EGARCH model. After removing predictable components explained by corporate fundamentals and macro sentiment via first-stage regression, residual series are adopted as purified inputs for asymmetric volatility modeling. The extracted conditional volatility acts as the core proxy for policy-driven market risks [7].

3.2.3 Control variables

Micro control variables: Firm size (natural logarithm of total assets), asset-liability ratio and return on assets, to control inherent risk differences across firms.

Macro control variable: CBOE Volatility Index (VIX), absorbing the impacts of global investor panic and systemic market fluctuations [2].

3.3 Disclosure of Core Empirical Parameters

All fixed parameters of the reproducible RStudio workflow are fully disclosed for replication [9].

Volatility model: Univariate EGARCH (1,1) estimated via maximum likelihood for individual stocks using the `rugarch` package [6].

Rolling window settings: Benchmark window length of 500 trading days with a one-day rolling step; 300-day and 800-day windows are set for robustness inspection.

Bootstrap settings: Resampling by continuous 22-day trading with 2,000 repeated iterations for standard error correction [7].

Stress testing settings: 99% confidence level for VaR and CVaR, 250-day out-of-sample forecasting window for backtesting [6].

4. Empirical Methodology: Standardized Two-Stage GARCH-DID Framework in RStudio

All estimation, simulation and robustness tests rely on open-source R quantitative packages, covering three core modules: two-way fixed-effects panel residual extraction, EGARCH asymmetric volatility estimation embedded with DID, and rolling-window dynamic stress testing with complete backtesting standards [9].

4.1 Stage 1: Two-Way Fixed-Effect Panel Regression for Residual Extraction

The first-stage regression simultaneously absorbs firm

fixed effects and time fixed effects, strips out fluctuations driven by observable corporate characteristics and global macro sentiment, and extracts orthogonal residual series free of endogenous interference. Residual data eliminates static cross-firm disparities and periodic market cyclical shocks, retaining only volatility components affected by exogenous overseas liquidity policies as clean inputs for second-stage modeling [7].

4.2 Stage 2: EGARCH Model Embedded with DID Interaction Terms

The baseline EGARCH model well captures the asymmetric leverage feature that negative news triggers larger volatility shocks [6]. This paper innovatively inserts baseline DID interaction terms and triple news interaction terms into volatility estimation, simultaneously measuring the overall volatility smoothing effect of liquidity policies and their marginal inhibitory effects on asymmetric leverage risks [8].

Due to generated regressor bias arising from first-stage residuals, block bootstrap correction is adopted: continuous 22-day trading blocks are taken as resampling units to maintain time-series volatility clustering characteristics. The complete two-stage estimation process is repeated 2,000 times for each sampling sample, and the empirical distribution of sampling coefficients replaces traditional asymptotic standard errors for all significance judgments [7].

4.3 RStudio Dynamic Rolling-Window Stress Testing Workflow

Recursive rolling estimation: Fixed-length rolling windows are used to re-estimate EGARCH model parameters every trading day, dynamically updating volatility persistence and asymmetric leverage coefficients to avoid bias caused by static full-sample fixed parameters. Multiple window lengths are set for robustness comparison [6]. Global extreme shock scenarios: Three sets of realistic crisis simulation frameworks are constructed: sharp VIX surge shock, US dollar liquidity tightening shock and global equity crash shock, with clear quantitative shock magnitudes specified for each scenario [2].

Multi-dimensional tail risk evaluation: Calculate out-of-sample forecasting errors of VaR and CVaR including MAE and RMSE; introduce three regulatory backtesting standards: Kupiec unconditional coverage test, Christoffersen joint conditional coverage test and Berkowitz density fitting test, to comprehensively compare the tail risk measurement accuracy of static and dynamic stress testing schemes [6].

5. Empirical Results and Analysis

5.1 Descriptive Statistics, PSM Balance Test and Parallel Trend Test

This paper reports the mean, standard deviation, extreme values, skewness and kurtosis of all core variables to depict the fat-tailed distribution characteristics of financial volatility data.

PSM matching results show the standardized mean difference of all covariates drops below 0.05 after matching, meaning characteristic gaps between the treatment and control groups are statistically eliminated, satisfying the matching premise of DID estimation [4].

Independent event-study parallel trend test results indicate all coefficient estimates for the 12 pre-policy periods are insignificant and fluctuate around zero, proving the treatment and control groups maintain consistent volatility trends without policy interference and meeting the core identification assumption of quasi-natural experiments [4].

5.2 Baseline Regression Results of Volatility Smoothing Effect

Corrected by bootstrap standard errors, the core TREAT×POST interaction coefficient is significantly negative at the 1% significance level. Economically speaking, the 2020 Fed liquidity easing reduces the conditional volatility of firms with high foreign capital exposure by an average of 14.7%. Loose global liquidity optimizes cross-border capital circulation via Stock Connect channels, alleviates secondary market liquidity shortages, and suppresses the frequency and amplitude of stock price fluctuations, fully supporting Hypothesis H1 [1].

5.3 Regression Results of Asymmetric Leverage Risk Mitigation

The triple interaction term coefficient is significantly negative at the 5% significance level. Without sufficient overseas liquidity buffers, negative news generates strong volatility amplification; after liquidity easing, the gap in asymmetric volatility responses between positive and negative news narrows by nearly 40%. Abundant cross-border capital acts as a systemic buffer against panic trading and weakens the asymmetric downside tail risk features of cross-border listed firms, verifying Hypothesis H2 [5].

5.4 Comparative Performance Results of Stress Testing

Dynamic EGARCH stress testing yields far lower MAE and RMSE of out-of-sample VaR and CVaR forecasts than static historical stress testing. Static schemes fail Kupiec and Christoffersen backtesting with severe bias of underestimating tail risks; rolling dynamic models pass all stan-

dard regulatory backtesting indicators, capture real-time volatility changes and heterogeneous policy responses amid shifting global liquidity cycles, and significantly improve the accuracy of extreme risk measurement, which confirms Hypothesis H3 [6].

6. Multi-Dimensional Robustness Tests

6.1 Double-Layer Random Placebo Test

Two independent randomization designs are adopted to rule out spurious regression:

Random policy timing test: Randomly assign virtual policy shock time points within the sample range, re-run the complete two-stage GARCH-DID process for each virtual time node, and all virtual DID coefficients are insignificant and distributed around zero [4].

Random grouping test: Randomly reassign labels of high/low foreign capital treatment groups while fixing the real policy timing, and all random interaction terms lose statistical significance.

Joint results of the double-layer placebo test prove that the significant volatility smoothing and risk mitigation effects solely stem from real overseas liquidity policy shocks, rather than inherent market trends or random sample noise [4].

6.2 Two-Way Clustered Robust Standard Error Correction

Traditional panel regression standard errors are distorted due to cross-sectional correlation across stocks and serial correlation within individual stocks. This paper uses the sandwich package to implement double clustering adjustment by stock code and trading date. After error correction, the sign, magnitude and significance of all core policy coefficients remain consistent with baseline regression results. Combined with block bootstrap correction in the second stage, dual statistical bias adjustment tools fully resolve interference from sequential estimation and panel correlation [7].

6.3 Inspection of Alternative Rolling Windows

Replace the benchmark 500-day rolling window with 300-day and 800-day windows for repeated EGARCH estimation and stress testing backtesting. The direction, significance and economic interpretation of core coefficients remain stable under different window lengths, demonstrating that research conclusions are not affected by arbitrary window selection and possess strong universality [6, 10].

7. Conclusion

Based on the global financial cycle theory and asymmet-

ric volatility theory, this paper develops a replicable two-stage GARCH-DID empirical framework using open-source RStudio. It systematically explores the causal spillover impacts of overseas liquidity shocks on volatility and asymmetric tail risks in A-share and Hong Kong stock markets for cross-border listed firms, and further compares the predictive performance of two stress-testing approaches. Consistent with the three research hypotheses, this paper draws three major conclusions as follows.

First, accommodative overseas liquidity policies exert a significant volatility-smoothing effect on cross-border A+H listed companies, markedly lowering the time-varying volatility of firms with high foreign capital dependence. Nevertheless, this effect is only valid for the liquidity easing episode within the 2018–2022 sample period and does not hold for liquidity-tightening cycles.

Second, ample global liquidity alleviates the asymmetric leverage effect across markets. It reduces the volatility amplification driven by negative news and improves the tail-risk profile of cross-border listed enterprises.

Third, the rolling-window dynamic EGARCH stress-testing method delivers better performance than conventional static historical stress testing. It satisfies regulatory backtesting requirements and substantially lowers prediction errors for extreme risks.

Furthermore, the two-stage hybrid empirical framework proposed in this paper mitigates endogeneity concerns prevalent in conventional volatility spillover studies. The fully annotated, reproducible R code offered in this paper can serve as a unified technical paradigm for future quantitative research on cross-border market risks.

From a regulatory perspective, authorities should phase out outdated static risk monitoring tools and implement R-based dynamic volatility stress-testing systems adapted to the Stock Connect scheme. Regulators may set tiered risk-warning thresholds based on listed firms' foreign ownership ratios, dynamically adjust cross-border capital access limits amid global liquidity tightening, and mandate financial institutions to perform standardized dynamic GARCH stress testing and regulatory backtesting on a regular basis. Looking ahead, financial regulators should further improve the cross-border risk early warning system matching the opening-up of China's capital market. With the continuous expansion of Stock Connect trading scales and increasing cross-border capital mobility, policymakers need to establish a long-term dynamic supervision mechanism targeting global liquidity shocks. Future policy formulation should fully consider the heterogeneous spillover characteristics of international monetary cycles on dual-listed enterprises, optimize cross-market risk linkage supervision rules, and build a more comprehensive and forward-looking cross-border financial risk prevention system to enhance the resilience of China's cross-border capital market against external shocks.

For securities firms, asset managers and cross-border investment banks, it is advisable to phase out legacy static stress-testing systems and build automated dynamic risk-measurement workflows. This enables real-time estimation of time-varying volatility and precise computation of VaR and CVaR metrics, supports rational internal risk-capital allocation, and facilitates regular simulation of compound crisis scenarios featuring liquidity tightening and global market panic.

For investors, positions in A+H listed firms with high foreign-capital exposure should be reduced during overseas liquidity-tightening cycles. Investors are suggested to dynamically adjust asset allocation in response to global liquidity conditions, and set stop-loss thresholds based on outputs from dynamic volatility models, so as to avoid heavy losses arising from cross-border risk contagion via the Stock Connect channels.

Despite the rigorous empirical design and robust findings of this study, several limitations remain to be addressed in future research. First, this paper restricts its research sample to A+H cross-border listed enterprises during 2018–2022, without covering other types of cross-border listed firms and longer time-series intervals. The heterogeneity of shock spillover effects on different industry sectors and firm-scale groups is not further subdivided and discussed. Second, this study mainly focuses on the volatility and tail risk spillover of global liquidity shocks, while ignoring the potential transmission mechanism of intermediate variables such as cross-border capital flows, investor sentiment and exchange rate fluctuations. Third, the empirical framework adopted in this paper focuses on linear causal identification and risk prediction, and fails to capture the nonlinear mutation characteristics and extreme systemic risk resonance under extreme global financial crisis scenarios. Future studies can expand the research sample, enrich mechanism analysis, adopt more advanced nonlinear econometric models, and further explore the multi-dimensional cross-border risk transmission paths to supplement and improve the research findings of this paper.

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