Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

From Anticipation to Implementation: Time–Frequency Reconfiguration of the Carbon–Freight Nexus under the EU ETS

Veranika Khlud

veranika.khlud@rtu.lv

Riga Technical University

Abdullah Açık

Dokuz Eylül University

Research Article

Keywords: EU Emissions Trading System, EU allowance futures, Baltic Dry Index, dry-bulk shipping, wavelet coherence, FuelEU Maritime

Posted Date: November 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11691579/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

From Anticipation to Implementation: Time–Frequency Reconfiguration of the Carbon–Freight Nexus under the EU ETS

Running head: Carbon prices and dry freight

Abstract

This study examines how the relationship between European Union allowance (EUA) prices and dry-bulk freight returns changes as maritime carbon regulation moves from anticipation to implementation. The analysis uses 714 weekly observations from January 2013 to September 2026 and applies wavelet coherence and phase-difference methods across four regulatory stages: pre–Fit for 55, the 2021–2023 transition, maritime inclusion in the EU Emissions Trading System in 2024, and the subsequent EU ETS–FuelEU Maritime period. Despite a near-zero full-sample return correlation, local dependence differs in sign and horizon. Positive EUA-leading configurations dominate statistically significant 2–8-week cells during 2021–2024. In 2025–2026, statistically significant 8–32-week coherence is predominantly negative and EUA-leading. These configurations remain visible under alternative wavelet resolution, winsorization and Brent-adjusted partial coherence, although a 1% threshold sharply reduces significant coverage. The findings show that maritime carbon-market integration is characterized by a reconfiguration of the carbon–freight relationship rather than a uniform strengthening. For shipping businesses and policy analysis, the results underline the need to distinguish allowance exposure, freight-market conditions and the horizon over which market information is incorporated.

Keywords: EU Emissions Trading System; EU allowance futures; Baltic Dry Index; dry-bulk shipping; wavelet coherence; FuelEU Maritime

1 Introduction

The inclusion of maritime transport in the European Union Emissions Trading System (EU ETS) makes carbon allowances relevant to shipping costs, but it does not establish how allowance-price changes translate into freight-market outcomes. A compliance cost incurred on a covered voyage, the amount recovered through a contract, and a movement in a global freight index are different economic quantities. Their relationship depends on market conditions and the allocation of costs between shipping companies, charterers and cargo interests. Existing maritime research consequently distinguishes the regulatory obligation from its commercial incidence across shipping segments (Christodoulou and Cullinane 2024; Flodén et al. 2024). The empirical question is not simply whether carbon becomes more expensive for shipping, but whether carbon and freight markets display a stable relationship as that exposure develops.

The regulatory sequence provides a useful setting for examining this question. The Fit for 55 package was presented on 14 July 2021, whereas maritime EU ETS coverage began on 1 January 2024 (Council of the European Union 2023; European Commission 2025). The surrender obligation covers 40% of eligible emissions generated in 2024, 70% in 2025 and

100% from 2026; surrender occurs in the following year. FuelEU Maritime applies from 1 January 2025 and regulates the greenhouse-gas intensity of energy used on board, rather than establishing a separate allowance price (European Parliament and Council 2023). These milestones distinguish announcement, preparation and operational compliance. They do not, however, constitute isolated experiments: policy development overlaps with other changes affecting carbon, energy and freight markets.

There is already direct evidence on carbon–shipping interdependence. Meng et al. (2023a) examine carbon and shipping markets using wavelet and spillover methods, while Melas, Michail, and Tsinaslanidis (2026) analyse carbon pricing, freight rates and inflation using observations covering the initial implementation period. The contribution sought here is therefore not the first connection between the two markets, nor the introduction of a new wavelet estimator. It is a regulatory-stage comparison extending through September 2026, asking whether the sign and horizon of dependence observed during anticipation remain visible once maritime coverage and the subsequent regulatory framework are operating. This distinction matters because an average association can obscure local relationships of opposite sign.

Against this background, this study examines whether the relationship between EU allowance (EUA) futures returns and Baltic Dry Index (BDI) returns changes across four regulatory periods. Weekly observations from 2013 to 2026 are analysed using wavelet coherence and phase differences. The approach identifies when the two series are coherent, at which horizons, and their relative phase within statistically significant regions. It does not estimate a causal policy effect, a structural carbon-cost elasticity or an out-of-sample forecasting relationship. Moreover, the BDI is a global dry-bulk benchmark, not an index of Baltic Sea routes or of exclusively EU ETS-covered voyages. Its use therefore addresses market interdependence rather than the direct incidence of compliance costs on a representative regulated voyage.

Accordingly, the study addresses the following research questions:

RQ1. How does the time–frequency relationship between EU allowance prices and BDI returns vary across short-, medium-, and longer-term horizons?

RQ2. Does the relationship differ across the pre–Fit for 55, regulatory-transition, initial maritime EU ETS, and subsequent EU ETS–FuelEU periods?

RQ3. Within statistically significant time–frequency regions, do EU allowance prices tend to lead BDI returns, and does the sign and horizon of this relationship change across regulatory stages?

The study contributes in three related ways. First, it distinguishes anticipation from successive implementation stages within a common weekly dataset. Second, it separates coherence strength, significant coverage and phase composition, avoiding the assumption that increased regulatory exposure must strengthen every measure of dependence. Third, it examines whether the principal configurations survive changes in wavelet resolution, treatment of extreme returns, significance thresholds and adjustment for Brent returns. The resulting evidence is relevant to maritime commercial analysis because it differentiates short-horizon positive co-movement from medium-horizon negative configurations without equating either with verified cost transmission. The remainder of the paper reviews the literature, presents the data and methods, reports the results, and discusses their economic interpretation and limitations.

2 Literature review

2.1 Carbon regulation, shipping costs and commercial incidence

Research on maritime emissions trading initially concentrated on regulatory design, abatement incentives and the distribution of compliance costs. Christodoulou and Cullinane (2024), writing in Maritime Economics & Logistics, assess the prospects and implications of shipping emissions trading and stress that outcomes depend on the characteristics of shipping markets. Their analysis provides an institutional basis for expecting heterogeneous responses rather than a uniform freight-price effect. For the present study, the relevant implication is that the transition into a common carbon market can change commercial exposure without mechanically generating a stable positive correlation between allowance and freight returns.

Flodén et al. (2024) combine emissions data, calculations and stakeholder interviews to assess maritime EU ETS implications for mitigation, costs and modal competition. They anticipate short-run cost recovery through surcharges and identify differences across vessel segments and abatement options. These are assessments of expected adjustment, not estimates of a realized carbon-price elasticity of the BDI. Distinguishing the two is important: a separately charged compliance surcharge and the underlying charter-market assessment need not move together. Similarly, findings on competition between short-sea services and land transport cannot automatically be transferred to global deep-sea dry-bulk markets.

A vector autoregressive analysis of Fit for 55 links marine fuel prices to Ireland’s maritime sector and macroeconomy (Ahearne and Cassidy 2025). Their projections illustrate how fuel-cost changes may affect sectoral activity and trade while producing a different scale of response in aggregate economic indicators. The study is relevant to the distinction between sectoral exposure and economy-wide outcomes, but its national setting and projected transition

should not be read as observed global dry-bulk market effects. Together, these studies establish the economic importance of cost allocation and adjustment, while leaving room for market-based evidence on the timing and sign of carbon–freight dependence.

2.2 Carbon, energy and shipping-market interdependence

The allowance price is not a shipping-specific cost shock. Aatola, Ollikainen, and Toppinen (2013) relate EUA forward prices to market fundamentals, including electricity and the gas–coal price differential, using the early EU ETS period. Their findings explain why carbon prices may reflect developments outside shipping. Consequently, co-movement with freight can arise through common economic or energy conditions even before shipping is subject to allowance surrender. An empirical comparison must therefore distinguish the existence of market linkages from the proposition that maritime regulation created them.

Meng et al. (2023a) provide the closest methodological and substantive precedent. Combining wavelet analysis with spillover indices, they identify time-varying dependence between carbon finance and shipping, stronger links with dry bulk than with tankers, and asymmetric information transmission. Their evidence rules out treating carbon–freight time–frequency analysis itself as a new contribution. It also supports examining whether previously observed dependence remains concentrated at the same horizons during maritime implementation. The present analysis extends this question through explicit regulatory-stage summaries and a later sample, rather than claiming to supersede their multisegment spillover framework.

Related work demonstrates the importance of energy-market interactions. Meng et al. (2023b) examine carbon markets and marine fuel markets across geographical locations and find that short-term spillovers and their direction differ across markets. Direct and indirect linkages between carbon, energy and shipping markets, including channels involving crude oil, have also been identified using quantile connectedness and mixed-frequency volatility methods (Chen, Feng, and Mi 2024). These studies motivate the Brent-controlled robustness exercise below. They also show why Brent alone cannot represent the entire energy environment: crude oil, bunker fuel, natural gas and coal are not interchangeable exposures.

Recent early-implementation evidence finds no statistically significant increase in freight rates or inflation following higher carbon prices over the January 2023–August 2024 period (Melas, Michail, and Tsinaslanidis 2026). The authors interpret the evidence through a “Silent Absorber” hypothesis. The present study asks a different question: whether local phase configurations vary across time scales and later implementation stages. A negative medium-horizon phase configuration does not independently verify cost absorption, just as an

insignificant average response does not exclude episodic coherence. Differences in sample coverage, variables and estimands must be retained when comparing the findings.

2.3 Time–frequency evidence and the remaining research question

Wavelet methods separate time-localized dependence from its frequency composition. Torrence and Compo (1998) establish the practical continuous-wavelet framework, while Grinsted, Moore, and Jevrejeva (2004) distinguish cross-wavelet power from normalized wavelet coherence. Applications to stock returns and energy commodities show the value of examining relationships at multiple horizons rather than through a single full-sample coefficient (Rua and Nunes 2009; Vacha and Barunik 2012). Partial wavelet coherence extends this framework by estimating local dependence between two series after conditioning on a third (Ng and Chan 2012), and Wu et al. (2020) illustrate its use for oil-related financial-market co-movement. These are established tools adopted here, not methodological innovations of this paper.

Their interpretation nevertheless requires care. Local significance does not demonstrate that an entire map is significant, and a visually prominent patch is not automatically evidence of a distinct economic mechanism (Maraun and Kurths 2004). Phase ordering is not structural causality; a wavelet period is not an estimated transmission delay. The literature therefore motivates a bounded research question: do the observed carbon–freight configurations differ across the selected regulatory stages, and how sensitive are those descriptions to the analytical choices? The study addresses that question without imposing a directional hypothesis inferred retrospectively from the results, or treating the policy dates as independently identified structural breaks.

3 Data and methodology

3.1 Data and variable construction

The empirical analysis uses weekly EUA futures prices and the BDI from 6 January 2013 to 6 September 2026. The EUA measure is the continuous Carbon Emissions Futures historical series distributed by Investing.com, quoted in euros; the BDI series is the provider’s weekly historical benchmark for global dry-bulk freight-market conditions (Investing.com 2026a, 2026b). The dataset contains 714 aligned level observations for each variable. The downloaded source files are dated 13 September 2026.

The observations are indexed by Sunday and spaced at exactly seven-day intervals. When the underlying market observation falls on a business day, the most recent value within the same

calendar week is assigned to the Sunday label. This procedure preserves weekly alignment without using information from a later week. Both variables are transformed into continuously compounded weekly percentage changes:

$$r_{i,t} = 100\left[\ln\left(P_{i,t}\right) - \ln\left(P_{i,t-1}\right)\right] = 100\Delta\ln\left(P_{i,t}\right), \quad (1)$$

Here, P denotes either the EUA price or the BDI, and t denotes the observation week. The transformation requires one lagged level, leaving 713 returns. "BDI returns" refers to changes in the index, not returns earned on a directly tradable asset. The weekly alignment reduces, but does not eliminate, differences in the timing of market observations.

Table 1 reports the level statistics. EUA prices have a mean of 37.574 and range from 3.050 to 98.010; the BDI has a mean of 1,467.597 and ranges from 291 to 5,526. Their standard deviations in levels are not directly comparable because their units differ. Pearson and Spearman level correlations are 0.547 and 0.574, respectively. These correlations may reflect persistent movements and are used only as descriptive evidence.

[Insert Table 1 about here]

Table 2 and Figure 1 describe the return series. Weekly BDI returns are more volatile than EUA returns, with standard deviations of 10.734% and 6.315%, respectively. Both distributions exhibit excess kurtosis, and Jarque–Bera tests reject normality. In contrast to the level correlations, full-sample return correlations are close to zero: Pearson's coefficient is 0.059 and Spearman's is 0.039. Positive and negative local relationships may offset in these summary coefficients, motivating the time–frequency analysis.

[Insert Table 2 about here]

[Insert Figure 1 about here]

The BDI aggregates global dry-bulk charter-market assessments. Its composition changed on 1 March 2018 to weights of 40% Capesize, 30% Panamax and 30% Supramax, with Handysize removed (Baltic Exchange 2018). The published benchmark is retained, but this change is relevant when comparing the early and later sample. Neither the index composition nor its global coverage permits identification of the proportion of each observation directly exposed to maritime EU ETS obligations.

3.2 Preliminary statistical analysis

Stationarity is evaluated using the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests. ADF and PP test a unit-root null, whereas KPSS tests stationarity. For logarithmic levels, ADF and PP include an intercept and deterministic trend, and KPSS tests trend stationarity. For returns, the specifications include an

intercept without a trend and KPSS tests level stationarity. ADF lag lengths are selected by the Bayesian Information Criterion from a maximum of 20 lags. PP uses the Z-tau statistic with the short truncation rule; the corresponding short KPSS bandwidth is six lags. The tests were implemented in R 4.6.1 using urca 1.3-4.

Table 3 indicates non-stationarity in logarithmic EUA levels. For logarithmic BDI levels, ADF and PP reject a unit root while KPSS rejects trend stationarity, giving mixed evidence. All three tests support the use of returns: ADF and PP reject a unit root at 1%, and KPSS does not reject level stationarity. Transforming the series therefore reduces the risk that persistent level movements dominate the coherence results, without implying that the return distributions or their dependence are constant throughout the sample.

[Insert Table 3 about here]

3.3 Wavelet coherence and phase-difference analysis

Wavelet coherence is used to examine whether the relationship changes across time and horizons. For a time series x(t), the continuous wavelet transform is defined as:

$$W_x(u,s) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-u}{s} \right) dt, \quad (2)$$

Here, u denotes time location, s is scale, and the asterisk denotes complex conjugation. The complex Morlet mother wavelet is:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}, \quad (3)$$

The dimensionless central frequency is set to 6. This provides the time–frequency localization used in the established wavelet framework (Torrence and Compo 1998; Grinsted, Moore, and Jevrejeva 2004). With EUA returns entered as x and BDI returns as y, the cross-wavelet transform is:

$$W_{xy}(u,s) = W_x(u,s) W_y^*(u,s). \quad (4)$$

Squared wavelet coherence normalizes common local variation by the individual wavelet powers (Torrence and Webster 1999; Grinsted, Moore, and Jevrejeva 2004):

$$R_{xy}^2(u,s) = \frac{\left| S\left(s^{-1} W_{xy}(u,s) \right) \right|^2}{S(s^{-1}|W_x(u,s)|^2) S\left(s^{-1} \left| W_y(u,s) \right|^2 \right)}, \quad (5)$$

S denotes smoothing in time and scale. Squared coherence lies between zero and one and measures local dependence strength, not its sign. The phase difference is obtained from the argument of the complex cross-wavelet transform:

$$\phi_{xy}(u,s) = \operatorname{atan2}\left[\operatorname{Im}\{W_{xy}(u,s)\}, \operatorname{Re}\{W_{xy}(u,s)\} \right]. \quad (6)$$

The implementation uses biwavelet (Gouhier, Grinsted, and Simko 2024). Under its plotting convention, rightward components indicate in-phase dependence, leftward components anti-phase dependence, upward components EUA leadership and downward components BDI leadership. The reported positive and negative EUA-leading categories follow that convention within significant regions. These labels describe relative phase, not structural causality. In particular, anti-phase ordering is sensitive to the phase branch and cannot by itself identify an unambiguous economic delay; a period of 8–32 weeks does not mean that an allowance-price shock affects freight precisely 8–32 weeks later.

Statistical significance is evaluated against an AR(1) red-noise null using 1,000 Monte Carlo surrogate replications. The AR(1) coefficients are estimated separately for the two return series; the baseline pointwise significance level is 5%. Boundary effects are handled using the cone of influence (COI): quantitative summaries retain only edge-unaffected cells, where the Fourier period does not exceed the local COI boundary. This definition avoids the ambiguous use of "inside" and "outside" the cone. Local tests remain subject to the interpretive limitations of wavelet significance testing (Maraun and Kurths 2004).

The sampling interval is one week. The baseline uses zero padding, scale resolution dj = 1/12, minimum scale $s_0 = 2$ and maximum scale 128. Scale and Fourier period are closely related but not identical for the Morlet wavelet; the reported horizon bands refer to periods in weeks. The coherence surface is summarized across the periods and bands described below. The same settings and edge-screening principle are used for the robustness comparisons unless expressly changed.

3.4 Regulatory periodization and time–frequency measures

Four periods are defined by the policy milestones in Table 4. The benchmark precedes the Fit for 55 announcement of 14 July 2021; it is not a period without carbon policy. The transition ends on 31 December 2023. The revised ETS legislation's entry into force on 5 June 2023 is marked in the figures but is not a separate subsample. The third period covers maritime EU ETS implementation in 2024, and the final period starts on 1 January 2025, alongside FuelEU Maritime. These dates describe regulatory stages rather than estimated structural breaks (Council of the European Union 2023; European Commission 2025; European Parliament and Council 2023).

[Insert Table 4 about here]

The continuous time–frequency domain is grouped into four descriptive bands: 2–8, 8–32, 32–64 and 64–128 weeks. For each stage and band, the summaries report mean squared coherence

across valid cells, the percentage of valid cells exceeding the significance threshold, and phase-category percentages among significant cells. Positive and negative EUA-leading shares use significant cells as their common denominator, not all valid cells or the number of calendar weeks. Their sum equals the total EUA-leading share apart from rounding.

These percentages are descriptive measures, not independent-observation probabilities, effect sizes or formal tests of differences between stages. Neighbouring wavelet cells are dependent. Moreover, wavelets centred near a stage boundary use observations on both sides, especially at longer periods. Interpretation therefore concentrates on the 2–8- and 8–32-week bands; longer-period estimates are additionally constrained by short post-implementation coverage and the COI. A smaller amount of valid long-period information near the sample end must not be interpreted as proof that longer-run dependence has disappeared.

3.5 Robustness checks

Four checks examine sensitivity without replacing the baseline research design. First, the scale grid is made coarser, changing dj from 1/12 to 1/8. Second, both return series are winsorized at their 1st and 99th percentiles. Third, the pointwise significance level is reduced from 5% to 1%. The original returns remain the baseline. Robustness is assessed separately for the direction of surviving phase configurations and the extent of statistically significant coverage; stability of one does not imply stability of the other.

Fourth, partial wavelet coherence conditions the EUA–BDI relationship on weekly Brent crude-oil returns. Europe Brent Spot Price FOB data, expressed in US dollars per barrel, were obtained from the U.S. Energy Information Administration (2026). The EIA weekly average for the Friday ending each observation week was assigned to the corresponding Sunday label, producing 714 aligned level observations and 713 weekly log returns. Partial wavelet coherence follows Ng and Chan (2012) and uses the same Morlet wavelet, scale grid, horizon bands and cone-of-influence rule as the baseline analysis.

Statistical significance is evaluated with 1,000 independent AR(1) surrogate triplets generated from the estimated persistence of EUA, BDI and Brent returns. At each scale, the 95th percentile of the simulated partial-coherence distribution is used as the critical value. Phase shares retain the original EUA–BDI phase among cells that remain significant after Brent adjustment. This robustness exercise tests whether the principal phase configurations remain visible after accounting for a major common energy-market factor; it does not re-estimate a structural cost pass-through coefficient.

4 Results

4.1 Overall time–frequency dependence

Figure 2 presents the wavelet coherence surface. Significant dependence occurs in separate clusters rather than continuously. Short-period episodes are visible around 2014, 2017–2018, 2020–2021 and 2023–2024, with further patches near the sample end. The 8–32-week band also contains localized regions, including episodes around 2014, 2018, 2022 and 2025–2026. These patterns are consistent with a small full-sample return correlation coexisting with more pronounced local dependence.

Longer-period coherence is most apparent in the earlier sample, especially in the mid-2010s and around 2019. Some of the longest-period features are edge-affected and excluded from numerical summaries. Post-2021 interpretation consequently focuses on short and medium horizons, without treating the limited later long-period coverage as evidence of an absence of persistent relationships.

[Insert Figure 2 about here]

4.2 Regulatory reconfiguration of the carbon–freight relationship

Table 5 does not show a uniform strengthening of coherence across stages. At 2–8 weeks, mean coherence remains between 0.30 and 0.32, while significant coverage ranges from 3.86% to 5.94%. The more pronounced change is in phase composition. Before Fit for 55, negative EUA-leading configurations account for 68.15% of significant cells and positive ones for 6.17%. During the 2021–2023 transition, these shares are 1.09% and 90.22%, respectively, with EUA-leading configurations comprising 91.30% in total.

In 2024, significant short-band coverage is 5.13%. All significant cells are classified as EUA-leading, and 96.88% are positive. This is a predominantly positive phase configuration among a relatively small subset of cells, not evidence of a positive relationship in 96.88% of all observations. Nor is significant coherence confined to the short band: the 8–32-week significant share in 2024 is 6.33%. In 2025–2026, short-band significant coverage falls to 4.29%, and EUA-leading configurations account for only 46.43% of significant cells.

At 8–32 weeks, significant coverage increases descriptively from 2.99% before Fit for 55 to 3.23% during transition, 6.33% in 2024 and 11.37% in 2025–2026. Mean coherence reaches 0.41 in the final stage. Under the baseline classification, all significant final-stage medium-band cells are negative and EUA-leading. Thus, the distinctive later configuration differs in both phase and horizon from the positive short-band pattern during 2021–2024. No formal test of equality across stages is implied by these comparisons.

[Insert Table 5 about here]

4.3 Phase differences and lead–lag dynamics

Figure 3 complements the coherence map by displaying phase arrows in significant regions. The positive short-horizon configuration during transition and initial implementation is associated with rightward and upward components under the stated biwavelet convention. The final-stage medium-horizon configuration instead has leftward and upward components. This is consistent with the reported shift from in-phase to anti-phase dependence. The figure and the table are two representations of the same estimates, not independent confirmations of a transmission mechanism.

The EUA-leading terminology is therefore interpreted as a phase classification conditional on coherent regions. It does not establish that market participants could have predicted subsequent BDI changes from EUA prices, that an economically identified shock originates in carbon regulation, or that the same ordering applies outside the significant regions. Anti-phase configurations require particular caution because different representations of a cycle can yield different descriptions of lead and lag.

[Insert Figure 3 about here]

4.4 Robustness results

Table 6 shows that the main phase configurations are relatively stable under alternative resolution and winsorization. The positive EUA-leading share at 2–8 weeks during transition is 90.22% in the baseline, 90.76% with the coarser grid and 91.87% after winsorization. Corresponding 2024 shares range from 93.94% to 97.30%. For 2025–2026 at 8–32 weeks, negative EUA-leading shares are 100%, 91.87% and 100%, respectively; significant coverage remains between 11.37% and 11.99%.

The 1% test gives an important qualification. Although the dominant phase categories remain, significant coverage falls to 1.65% for the transition short band, 0.56% for the 2024 short band and 0.46% for the 2025–2026 medium band. In the last case, a 100% negative share describes only this much smaller surviving subset. The results therefore support conditional stability of phase orientation more strongly than stability of the extent of significant dependence.

[Insert Table 6 about here]

Table 7 and Figure 4 report the Brent-adjusted results. During the 2021–2023 transition, mean partial coherence at 2–8 weeks is 0.209 and 4.81% of valid cells are significant. Among these cells, 81.88% are positive and EUA-leading. In 2024, mean partial coherence is 0.194, significant coverage is 3.04%, and 92.11% of significant cells are positive and EUA-leading.

Brent adjustment therefore preserves the sign and direction of the short-horizon configuration while reducing its significant coverage relative to the bivariate baseline.

During 2025–2026, mean partial coherence at 8–32 weeks is 0.373 and 18.84% of valid cells are significant. Negative EUA-leading configurations account for 94.44% of significant cells, while the total EUA-leading share is 94.79%. The medium-horizon phase reversal therefore remains visible after conditioning on Brent. Because partial and bivariate coherence are different conditional measures with different critical values, their significant shares are not interpreted as changes in structural effect size.

[Insert Table 7 about here]

[Insert Figure 4 about here]

5 Discussion

5.1 From regulatory anticipation to market incorporation

The results point to a changing composition of carbon–freight dependence, not a monotonic strengthening as shipping enters emissions trading. At short horizons, average coherence is almost unchanged across stages, even when the composition of significant cells moves from predominantly negative to positive EUA-leading configurations. The distinction between average strength and conditional phase composition is central to the interpretation. The study adds a description of how local relationships differ across the implementation sequence; it does not establish that a larger regulatory burden necessarily produces stronger aggregate integration.

This finding is compatible with the pre-existing carbon–shipping links documented by Meng et al. (2023a). The existence of early-sample coherence means that maritime compliance is not a necessary condition for the two markets to co-move. Carbon pricing can reflect wider energy and production conditions, while dry-bulk charter markets respond to global transport demand. The contribution of the present comparison is to locate a later change in the observed configuration, not to attribute the creation of the relationship to a single legislative event.

The transition from expectations to compliance is one plausible context for that change. Before implementation, prospective costs may enter commercial expectations without current maritime surrender obligations. After implementation, exposure depends additionally on covered voyages and the phase-in schedule. Yet the empirical stages bundle these developments with contemporaneous market conditions. In particular, the 2025–2026 window cannot separate the continuing ETS phase-in from FuelEU Maritime, a different regulatory

instrument. Its name identifies overlapping implementation dates, not an estimated FuelEU treatment effect.

5.2 Why does the relationship move from short to medium horizons?

Short-horizon positive co-movement can be consistent with relatively rapid changes in shared expectations, whereas medium-horizon dependence can be consistent with slower commercial adjustment. Decisions about allowance procurement, contract renewal or vessel employment need not occur at the same frequency. These are possible interpretations rather than mechanisms measured by this dataset. No contract records, allowance inventories, voyage durations or operational responses are observed, so the 2–8- and 8–32-week bands should not be assigned to particular decision cycles as an empirical finding.

The distinction between a wavelet period and a transmission delay is especially important. A band identifies the periodicity at which the series exhibit local dependence. It does not show that the commercial response takes the corresponding number of weeks. Likewise, a full-sample wavelet transform is an ex post analysis that uses information on both sides of a time location; its phase arrows cannot be converted directly into real-time trading signals. Establishing forecasting usefulness would require a separate evaluation with information available at each forecast date.

There is also a statistical reason for restraint. The later sample is short relative to long wavelet periods, and edge screening removes an increasing share of those cells near its end. Some apparent movement towards shorter horizons may therefore reflect the information available for reliable comparison. Within the reported short and medium bands, the later negative configuration survives the grid and outlier checks, but the 1% test leaves only 0.46% significant coverage. The evidence supports an identifiable local pattern, not a pervasive medium-term relationship operating throughout 2025–2026.

5.3 Economic interpretation of the change from positive to negative EUA-leading configurations

A positive phase configuration does not isolate carbon-cost pass-through. For example, stronger activity could be associated with both increased demand for freight and changing allowance demand, producing positive co-movement without a direct surcharge mechanism. Conversely, an allowance-price movement associated with supply or regulatory expectations need not accompany higher cargo demand. Because the analysis does not identify the source of allowance-price innovations, these channels remain observationally intertwined. The

established relationship between carbon prices and energy fundamentals reinforces this limitation (Aatola, Ollikainen, and Toppinen 2013).

The later negative configuration is consistent with several competing interpretations. Higher carbon-related costs could coincide with weaker transport demand or tighter charterer budgets; alternatively, the carbon and freight series could respond in opposite directions to a common disturbance. Contractual allocation may also distinguish gross voyage costs from the charter-market component represented by the BDI. None of these explanations is established by a negative phase angle. In particular, negative co-movement does not prove that shipping companies absorbed the compliance cost, earned lower profits, reduced emissions or changed sailing speed.

This is the relevant comparison with Melas, Michail, and Tsinaslanidis (2026). Their lack of a significant positive freight response cautions against assuming mechanical pass-through, but it estimates a different relationship over an earlier and shorter period. The present negative local configuration is not an independent confirmation of the Silent Absorber hypothesis. Similarly, the expected surcharges discussed by Flodén et al. (2024) concern a distinct contractual cost component and need not contradict an inverse relationship in a global charter-market index. The studies inform different parts of the commercial transmission question.

Brent adjustment helps distinguish a common oil-market channel. It reduces significant short-horizon coverage during the transition and in 2024, but the dominant positive EUA-leading phase remains. More importantly, the 2025–2026 negative medium-horizon configuration remains dominant after adjustment. Brent co-movement alone therefore does not account for the observed phase reconfiguration, although other energy, trade and macroeconomic channels may still contribute.

5.4 Implications for shipping-market participants and EU maritime carbon policy

For shipping companies and charterers, the practical implication is to distinguish allowance procurement exposure, contractual recovery of emissions costs and freight-market risk. A single historical correlation is a weak basis for assuming that those exposures offset one another. The different phase configurations in the estimates suggest that commercial monitoring should retain both the time horizon and the relevant freight segment. They do not establish an optimal hedge, a profitable trading rule or the proportion of compliance cost that can be recovered from customers. Such decisions require contract- and route-specific information beyond the BDI.

For assessment of maritime regulation, aggregate market co-movement is not a substitute for measuring compliance costs, emissions outcomes or changes in competitive conditions. The results identify where more targeted evidence may be useful: voyage-level exposure, charter terms and separate records of surcharges could distinguish direct cost allocation from broader freight-cycle effects. The comparison also cautions against treating a near-zero full-sample correlation as evidence that carbon and freight markets are unrelated. Conversely, a statistically significant patch does not measure the effectiveness or overall economic desirability of either regulatory instrument.

The findings should be read within the study's market-level scope. The BDI is a global benchmark that combines regulated and unregulated routes, and its composition changed in 2018. The post-implementation period is necessarily shorter than the pre–Fit for 55 sample, especially at longer horizons, and Brent represents one important energy-market control rather than the full macroeconomic environment. These features motivate future work with segment-specific freight indices, voyage-level exposure and longer post-implementation samples. They do not alter the central result that the sign and dominant horizon of local EUA–BDI dependence differ across the selected regulatory stages.

6 Conclusion

This study examined the relationship between weekly EUA futures and BDI returns from January 2013 to September 2026 using wavelet coherence and phase differences. Its aim was to compare the strength, sign, relative phase and horizon of dependence across regulatory anticipation and successive maritime implementation stages, without treating policy milestones as causal experiments.

The near-zero full-sample return correlation masks local dependence. Positive EUA-leading configurations dominate significant 2–8-week cells during 2021–2024. In 2025–2026, the distinctive configuration is negative and EUA-leading at 8–32 weeks. Alternative scale resolution and winsorization preserve this reconfiguration, while a stricter significance threshold reduces the extent of significant coverage. Brent-conditioned partial coherence also retains the main phase pattern: the positive short-horizon configuration remains visible in 2021–2024, and the later negative medium-horizon relationship remains dominant. The evidence therefore supports a change in sign and horizon rather than a uniform strengthening of carbon–freight dependence.

For maritime businesses, the results caution against treating allowance exposure and freight-market risk as a stable one-to-one relationship. Monitoring and risk management should

distinguish short-horizon market co-movement from medium-horizon adjustment and should account for contract and route characteristics. For policy analysis, the findings show that implementation can coincide with a reconfiguration of market interdependence even when average correlation is low. Further work with longer post-implementation samples and more disaggregated freight data can test the persistence and commercial mechanisms of this pattern.

References

Aatola, Piia, Markku Ollikainen, and Anne Toppinen. 2013. Price determination in the EU ETS market: Theory and econometric analysis with market fundamentals. *Energy Economics* 36: 380–395. https://doi.org/10.1016/j.eneco.2012.09.009.

Ahearne, Alan, and Daniel Cassidy. 2025. The impact of Fit for 55 on Ireland's maritime transport sector and the macroeconomy. *Maritime Economics & Logistics* 27: 25–49. https://doi.org/10.1057/s41278-023-00267-9.

Baltic Exchange. 2018. Baltic Exchange applies changes to BDI. https://www.balticexchange.com/en/news-and-events/news/press-releases-/2018/Baltic-Exchange-applies-changes-to-BDI1.html. Accessed 2 October 2026.

Chen, Yanhui, Ailing Feng, and Jackson Jinhong Mi. 2024. Does climate policy uncertainty drive the extreme spillovers of carbon-energy-shipping markets? *Journal of Environmental Management* 366: 121737. https://doi.org/10.1016/j.jenvman.2024.121737.

Christodoulou, Anastasia, and Kevin Cullinane. 2024. The prospects for, and implications of, emissions trading in shipping. *Maritime Economics & Logistics* 26: 168–184. https://doi.org/10.1057/s41278-023-00261-1.

Council of the European Union. 2023. 'Fit for 55': Council adopts key pieces of legislation delivering on 2030 climate targets. 25 April. https://www.consilium.europa.eu/en/press/press-releases/2023/04/25/fit-for-55-council-adopts-key-pieces-of-legislation-delivering-on-2030-climate-targets/. Accessed 2 October 2026.

European Commission. 2025. FAQ – Maritime transport in EU Emissions Trading System (ETS). https://climate.ec.europa.eu/areas-action/transport-decarbonisation/reducing-emissions-shipping-sector/faq-maritime-transport-eu-emissions-trading-system-ets_en. Accessed 2 October 2026.

European Parliament and Council. 2023. Regulation (EU) 2023/1805 of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union* L 234: 48–100. https://eur-lex.europa.eu/eli/reg/2023/1805/oj/eng.

Flodén, Jonas, Lars Zetterberg, Anastasia Christodoulou, Rasmus Parsmo, Erik Fridell, Julia Hansson, Johan Rootzén, and Johan Woxenius. 2024. Shipping in the EU emissions trading system: Implications for mitigation, costs and modal split. *Climate Policy* 24 (7): 969–987. https://doi.org/10.1080/14693062.2024.2309167.

Gouhier, T. C., A. Grinsted, and V. Simko. 2024. *R package biwavelet: Conduct Univariate and Bivariate Wavelet Analyses* (version 0.20.22). https://github.com/tgouhier/biwavelet.

Grinsted, A., J. C. Moore, and S. Jevrejeva. 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics* 11: 561–566. https://doi.org/10.5194/npg-11-561-2004.

Investing.com. 2026a. Carbon Emissions Futures historical data. https://tr.investing.com/commodities/carbon-emissions-historical-data. Accessed 13 September 2026.

Investing.com. 2026b. Baltic Dry Index historical data. https://tr.investing.com/indices/baltic-dry-historical-data. Accessed 13 September 2026.

Maraun, D., and J. Kurths. 2004. Cross wavelet analysis: Significance testing and pitfalls. *Nonlinear Processes in Geophysics* 11: 505–514. https://doi.org/10.5194/npg-11-505-2004.

Melas, Konstantinos D., Nektarios A. Michail, and Prodromos Tsinaslanidis. 2026. Shipping, carbon pricing, and inflation pass-through: The Silent Absorber hypothesis. *Research in Transportation Economics* 116: 101726. https://doi.org/10.1016/j.retrec.2026.101726.

Meng, Bin, Shuiyang Chen, Hercules Haralambides, Haibo Kuang, and Lidong Fan. 2023a. Information spillovers between carbon emissions trading prices and shipping markets: A time-frequency analysis. *Energy Economics* 120: 106604. https://doi.org/10.1016/j.eneco.2023.106604.

Meng, Bin, Bangguo Wei, Mo Yang, and Haibo Kuang. 2023b. Measuring the time-frequency spillover effect among carbon markets and shipping energy markets: A global perspective. *Energy Economics* 128: 107133. https://doi.org/10.1016/j.eneco.2023.107133.

Ng, Eric K. W., and Johnny C. L. Chan. 2012. Geophysical applications of partial wavelet coherence and multiple wavelet coherence. Journal of Atmospheric and Oceanic Technology 29 (12): 1845–1853. https://doi.org/10.1175/JTECH-D-12-00056.1.

Rua, António, and Luís C. Nunes. 2009. International comovement of stock market returns: A wavelet analysis. *Journal of Empirical Finance* 16 (4): 632–639. https://doi.org/10.1016/j.jempfin.2009.02.002.

Torrence, Christopher, and Gilbert P. Compo. 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society* 79 (1): 61–78. https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

Torrence, Christopher, and Peter J. Webster. 1999. Interdecadal changes in the ENSO–monsoon system. *Journal of Climate* 12 (8): 2679–2690. https://doi.org/10.1175/1520-0442(1999)012<2679:ICITEM>2.0.CO;2.

U.S. Energy Information Administration. 2026. Europe Brent Spot Price FOB (dollars per barrel), weekly. Petroleum & Other Liquids. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=RBRTE&f=W. Accessed 13 October 2026.

Vacha, Lukas, and Jozef Barunik. 2012. Co-movement of energy commodities revisited: Evidence from wavelet coherence analysis. *Energy Economics* 34 (1): 241–247. https://doi.org/10.1016/j.eneco.2011.10.007.

Wu, Kai, Jingran Zhu, Mingli Xu, and Lu Yang. 2020. Can crude oil drive the co-movement in the international stock market? Evidence from partial wavelet coherence analysis. *The North American Journal of Economics and Finance* 53: 101194. https://doi.org/10.1016/j.najef.2020.101194.

Table 1. Descriptive statistics of the level series

Statistic	EUA	BDI
Observations	714	714
Mean	37.574	1,467.597
Median	25.825	1,340.500
Standard deviation	31.769	765.891
Minimum	3.050	291.000
Maximum	98.010	5,526.000
Skewness	0.392	1.385
Kurtosis	1.484	6.025
Jarque–Bera	86.710	500.583
p-value	<0.001	<0.001

Note: EUA denotes EU allowance futures prices in euros; BDI is an index. Kurtosis is reported in its conventional form (normal distribution = 3).

Table 2. Descriptive statistics of weekly log returns

Statistic	EUA	BDI
Observations	713	713
Mean (%)	0.379	0.214
Median (%)	0.578	0.365
Standard deviation (%)	6.315	10.734
Minimum (%)	−41.294	−36.825
Maximum (%)	23.243	52.160
Skewness	−0.881	0.231
Kurtosis	8.517	4.760
Jarque–Bera	996.249	98.353
p-value	<0.001	<0.001

Note: Returns are 100 times the first difference of log levels. Kurtosis is reported in its conventional form (normal distribution = 3).

Table 3. Unit-root and stationarity tests

Series	Transform	ADF	Lag	PP (Z-tau)	KPSS	Conclusion
EUA	ln level	−1.785	1	−1.988	0.966***	Non-stationary
BDI	ln level	−4.675***	1	−4.024***	0.241***	Mixed evidence
EUA	Δln × 100	−19.752***	1	−26.705***	0.104	Stationary
BDI	Δln × 100	−14.948***	2	−18.569***	0.023	Stationary

Note: ADF and PP test a unit-root null; KPSS tests stationarity. Log-level specifications include an intercept and trend; return specifications include an intercept without a trend. ADF lags are selected by BIC from up to 20 lags. PP and KPSS use their short bandwidth rules. *** denotes rejection of the relevant null at 1%.

Table 4. Regulatory periods used in the analysis

Stage	Date range	Regulatory interpretation
Pre–Fit for 55	Before 14 July 2021	Benchmark before announcement; not a period without EU carbon policy
Transition	14 July 2021–31 December 2023	Policy anticipation and preparation for maritime EU ETS inclusion
Maritime ETS	1 January–31 December 2024	First maritime coverage year; 40% of eligible 2024 emissions to be surrendered in 2025
ETS + FuelEU	1 January 2025–end of sample	Continuing ETS phase-in alongside FuelEU Maritime application

Note: Dates are descriptive milestones, not estimated structural breaks. Sources: Council of the European Union (2023); European Commission (2025); European Parliament and Council (2023). The 2025–2026 stage does not separately identify the effects of the two instruments.

Table 5. Time–frequency coherence across regulatory periods

Stage	Band (weeks)	Mean coherence	Significant share (%)	EUA leads (%)	Positive EUA-leading (%)	Negative EUA-leading (%)
Pre–Fit for 55	2–8	0.32	3.86	74.32	6.17	68.15
Transition 2021–2023	2–8	0.31	5.94	91.30	90.22	1.09
Maritime ETS 2024	2–8	0.30	5.13	100.00	96.88	3.12
ETS + FuelEU 2025–2026	2–8	0.32	4.29	46.43	45.24	1.19
Pre–Fit for 55	8–32	0.32	2.99	59.47	31.56	27.91
Transition 2021–2023	8–32	0.31	3.23	63.00	18.00	45.00
Maritime ETS 2024	8–32	0.34	6.33	56.96	2.53	54.43
ETS + FuelEU 2025–2026	8–32	0.41	11.37	100.00	0.00	100.00

Note: All summaries exclude edge-affected cells. Significant share is the percentage of valid cells passing the 5% pointwise threshold (1,000 Monte Carlo replications). EUA-leading, positive and negative percentages have significant cells as their denominator. Phase labels follow the convention in Section 3.3 and are not causal effects or percentages of calendar weeks. Values are rounded; category shares may not sum exactly.

Table 6. Robustness of the principal time–frequency configurations

Specification	Stage	Band (weeks)	Significant share (%)	EUA leads (%)	Positive EUA-leading (%)	Negative EUA-leading (%)
Baseline: dj = 1/12, 5% test	Transition 2021–2023	2–8	5.94	91.30	90.22	1.09
Alternative: dj = 1/8	Transition 2021–2023	2–8	5.77	91.60	90.76	0.84
Winsorized 1–99%	Transition 2021–2023	2–8	6.75	92.34	91.87	0.48
1% significance test	Transition 2021–2023	2–8	1.65	94.12	94.12	0.00
Baseline: dj = 1/12, 5% test	ETS 2024	2–8	5.13	100.00	96.88	3.12
Alternative: dj = 1/8	ETS 2024	2–8	4.45	100.00	97.30	2.70
Winsorized 1–99%	ETS 2024	2–8	5.29	96.97	93.94	3.03
1% significance test	ETS 2024	2–8	0.56	100.00	100.00	0.00
Baseline: dj = 1/12, 5% test	ETS + FuelEU 2025–2026	8–32	11.37	100.00	0.00	100.00
Alternative: dj = 1/8	ETS + FuelEU 2025–2026	8–32	11.99	91.87	0.00	91.87
Winsorized 1–99%	ETS + FuelEU 2025–2026	8–32	11.82	100.00	0.00	100.00
1% significance test	ETS + FuelEU 2025–2026	8–32	0.46	100.00	0.00	100.00

Note: All specifications use 1,000 Monte Carlo replications and exclude edge-affected cells. Phase percentages are conditional on statistically significant coherence. “1% significance test” is the original 99% confidence specification. A stable phase percentage among surviving cells does not imply stable significant coverage.

Table 7. Brent-adjusted partial wavelet coherence

Stage	Band (weeks)	Mean partial coherence	Significant share (%)	EUA leads (%)	Positive EUA-leading (%)	Negative EUA-leading (%)
Transition 2021–2023	2–8	0.209	4.81	81.88	81.88	0.00
Maritime ETS 2024	2–8	0.194	3.04	97.37	92.11	5.26
ETS + FuelEU 2025–2026	8–32	0.373	18.84	94.79	0.35	94.44

Note: Partial coherence conditions weekly EUA–BDI dependence on EIA Brent spot-price returns. Statistical significance uses 1,000 independent AR(1) surrogate triplets and a scale-specific 95th-percentile threshold. All summaries exclude edge-affected cells. Phase percentages describe the original EUA–BDI phase among significant partial-coherence cells.

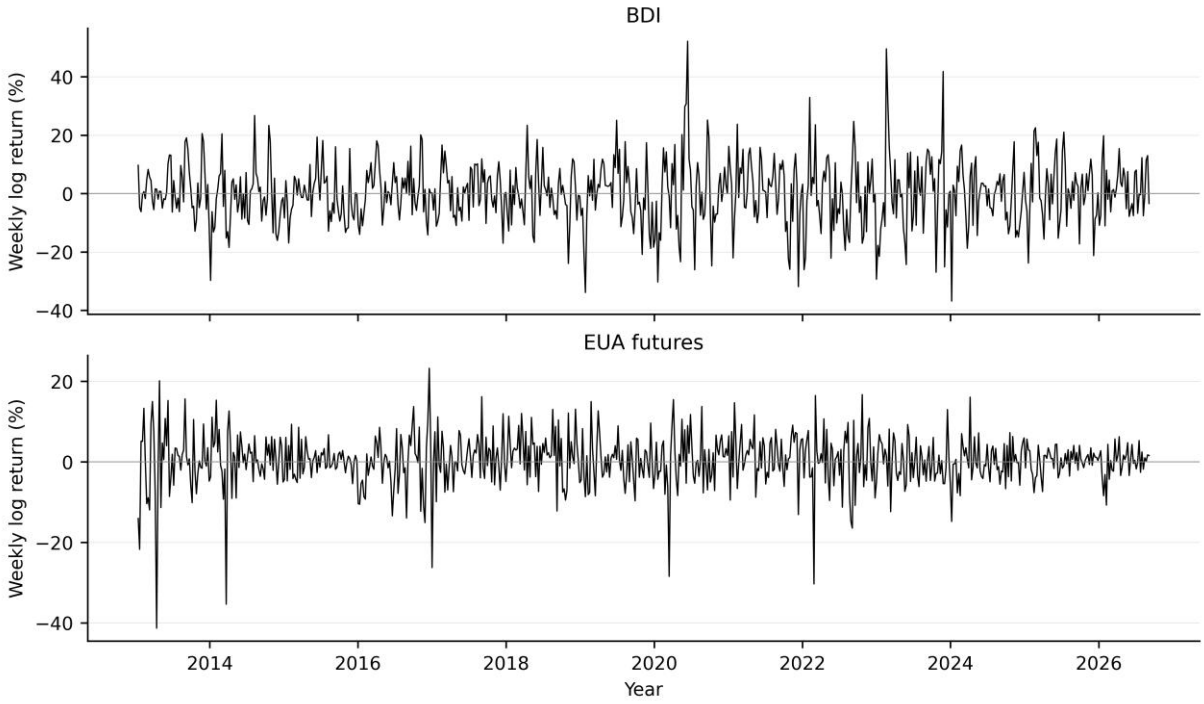

Figure 1. Weekly log returns of the Baltic Dry Index and EU allowance futures, 2013–2026.

Note: Returns are 100 times the first difference of log levels.

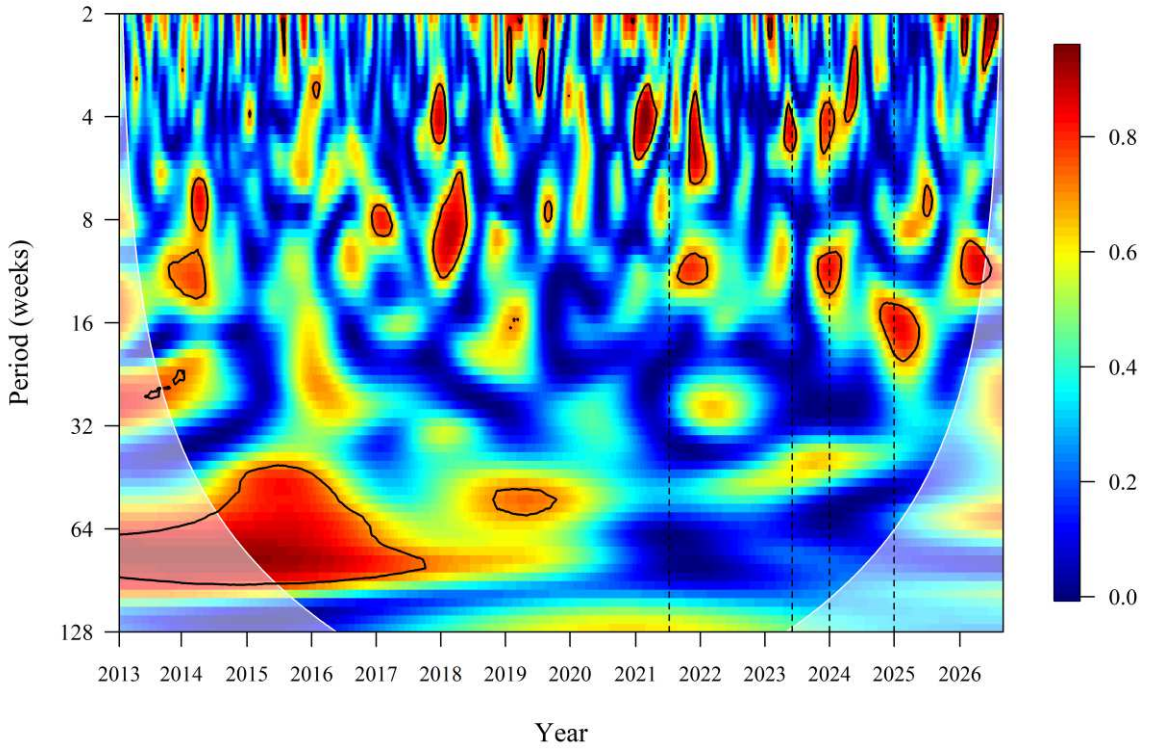

Figure 2. Wavelet coherence between weekly EUA futures and BDI returns.

Note: Warmer colours indicate higher squared coherence. Black contours indicate the 5% pointwise threshold from 1,000 Monte Carlo replications. The white COI boundary separates edge-unaffected shorter periods from edge-affected longer periods near the sample ends. Vertical dashed lines mark 14 July 2021, 5 June 2023, 1 January 2024 and 1 January 2025.

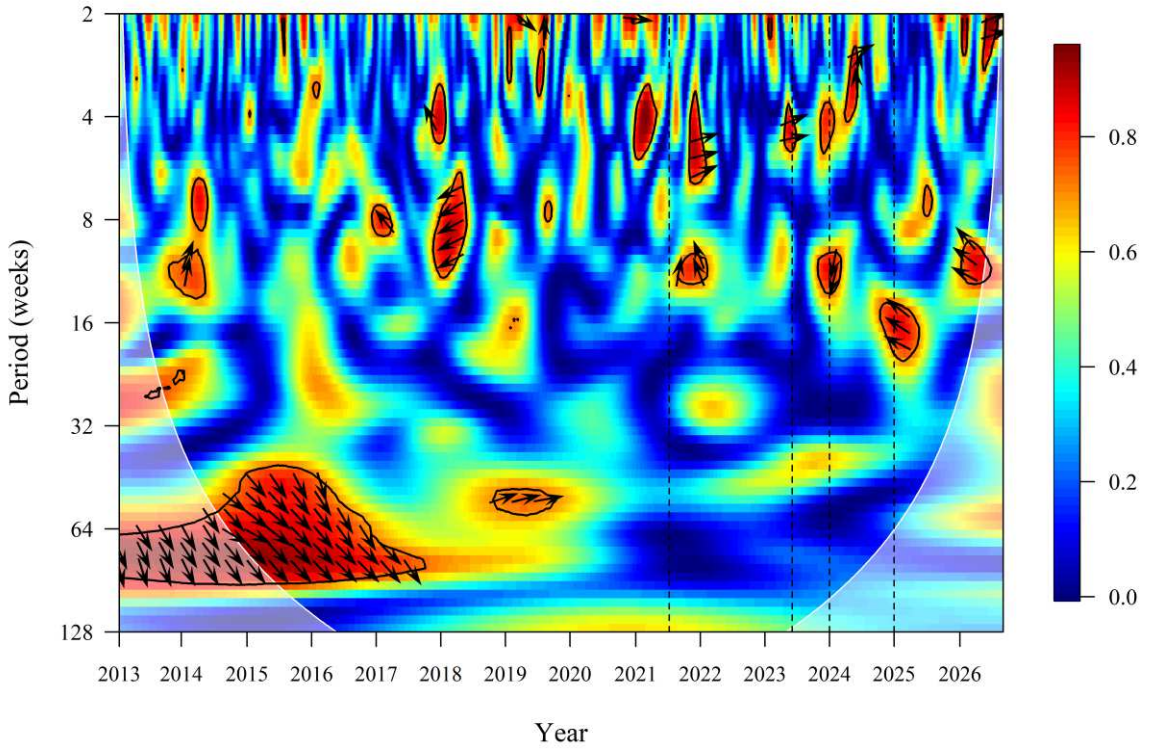

Figure 3. Wavelet coherence and phase differences between weekly EUA futures and BDI returns.

Note: Contours, COI and dates are as in Figure 2. Arrows display the original phase in significant regions. Under the biwavelet convention, right/left indicate in-phase/anti-phase dependence and up/down denote first-series/second-series leadership (EUA/BDI). Anti-phase leadership is convention-dependent and does not establish a causal delay.

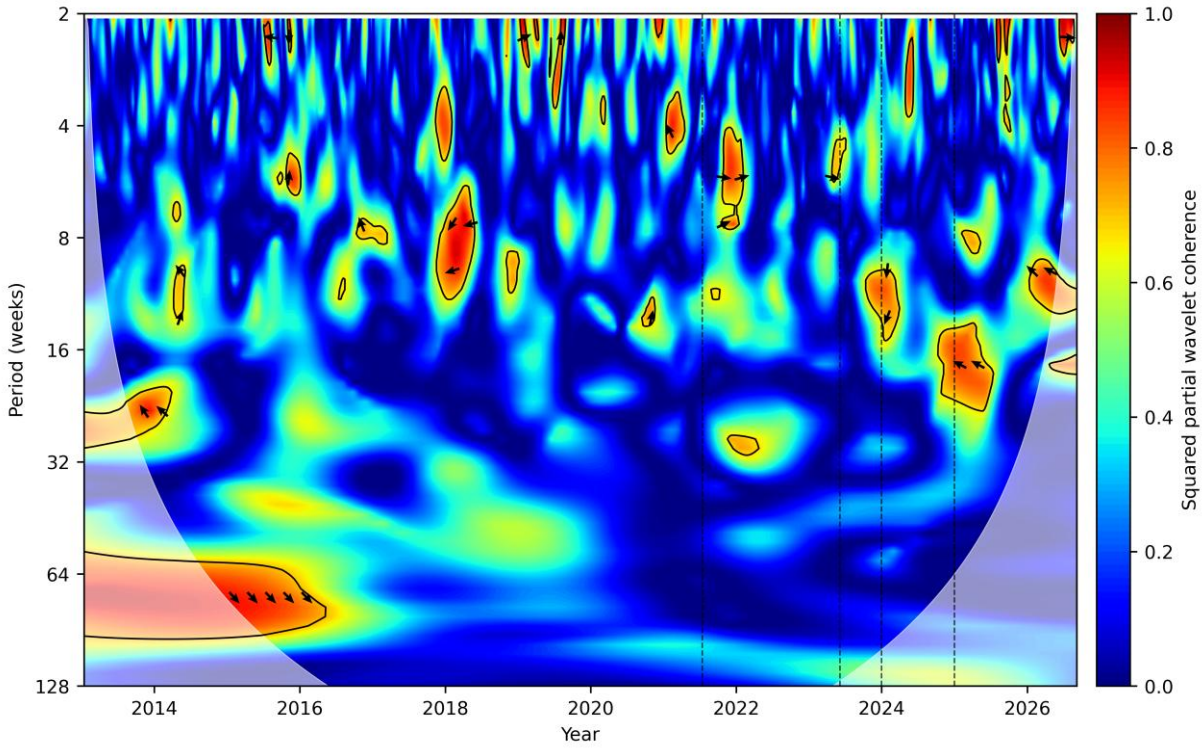

Figure 4. Partial wavelet coherence between weekly EUA futures and BDI returns after adjustment for Brent spot-price returns.

Note: Warmer colours indicate higher squared partial wavelet coherence. Black contours use the scale-specific 95th-percentile thresholds from 1,000 independent AR(1) surrogate triplets. The white shaded area is outside the cone of influence. Vertical dashed lines mark 14 July 2021, 5 June 2023, 1 January 2024 and 1 January 2025. Arrows retain the original EUA–BDI phase in significant, edge-unaffected cells.