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WAVELET-BASED INVESTIGATION OF AIR-PASSENGER TRANSPORT LINKAGES IN ASIAN EMERGING ECONOMIES: IMPLICATIONS FOR ENVIRONMENTAL MANAGEMENT AND ECONOMIC SUSTAINABILITY

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Abstract
This study investigates the time-varying spectral coherence of air-transportation in several Asian emerging economies (i.e. Indonesia, India, Iran, Malaysia, Pakistan, Singapore, Sri Lanka, Turkey, Korea, and Japan) focusing on the environmental economic implications. Employing a quantitative, time-series approach, and the study analyzes dynamic interdependencies within air-transportation data that are critical for environmental management and sustainable economic development. The dataset comprises sixty years of country-level air-transportation statistics sourced from the World Development Indicators, providing a comprehensive temporal perspective. Methodologically, wavelet analysis is utilized alongside descriptive statistics to uncover multi-scale patterns, using time-series graphs, individual and cross-wavelet power spectra, and wavelet coherence metrics, with special emphasis on Pakistan's linkage with other nations. Plots of air-passengers carried show a steady increase in numbers across all countries, led by Japan and Pakistan (notably in 2009/2010), and followed by a sharp rise until 2019. Individual wavelet power spectra reveal weak correlations at low frequencies, moderate to high correlations at middle frequencies, and strong correlations at high frequencies. Cross-wavelet spectra indicate weak co-movement at low frequencies, moderately strong co-movement at middle frequencies, and consistently high co-movement at high frequencies over the sample period. Wavelet coherence spectra display high coherence at low frequencies, mixed patterns at middle frequencies, and weak correlations at high frequencies, with noted edge effects between 2010 and 2019 at high frequency bands. Time-frequency results are broadly consistent, with certain bands showing higher coherence and correlation, confirming phase synchronization in the regions. This research offers novel insights into the environmental and economic sustainability of air-transport networks by applying advanced spectral techniques to emerging Asian markets. The findings provide valuable guidance for policymakers and industry stakeholders in designing regional environmental strategies and coordinating economic policies that balance the growth with ecological resilience in the air-transport sector.
Keywords: *Wavelet Analysis, Wavelet Coherence, Air-passenger Transport, Linkages in Asian Emerging Economies*

INTRODUCTION

Developing and dynamic economies in the Asian region are empowered by the economic development, global association, trade and ecological management through the air-transportation incorporating passenger and cargo facilities. A diverse sphere of nations encompassing Indonesia, India, Iran, Malaysia, Pakistan, Singapore, Sri Lanka, Turkey, Korea, and Japan that are essential to regional and global networks of air-transport is the aim of this research study which demonstrate the substantial environmental implications for geographic significance,

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different levels of economic development and strategic significance at the global level supply chains. Considering the air-transportation's time-varying spectral coherence among and within these nations is crucial for analyzing the versatile chemistry of economic forces, policy decisions, environmental demands, and external shocks decoding that are the main factors in shaping the related environmental impacts and air-transport sector. Air-transportation importance for these emerging Asian economies cannot be overelaborated for the reason that it boosts foreign direct investment, assists international trade through instant supporting of high-value and time-sensitive goods, empower knowledge-intensive industries and promotes tourism across borders (Nguyen, 2025; Rishan, et al., 2025; Mehdi et al., 2025). Integration of environmental challenges encompassing resource consumption, greenhouse gas emissions, and noise are essential to be integrated into economic frameworks that are influenced by the air-transport network simultaneously (Wang, et al., 2025; Spence, & Choi, 2025; Naeem et al., 2025). Air-transport encourages regional competitiveness, country's GDP by improving access to global market and saving transit time, however, ongoing policy reforms and infrastructure development must focus on minimizing environmental footprints and stabilizing economic integration (Bassem, 2025; Ali et al., 2025).

Over past decades, the volatility and significant growth experiences by the Asian air-transportation sector emphasizes this sector to be studied further. Notable investments in air traffic management, fleets and overall airport infrastructure is the ultimate demand in result of economic integration and swift globalization that accelerated air traffic volumes (Bassem, 2025; Ali et al., 2025). On the other hand, vulnerability to the external shocks such as geopolitical events, economic downturns and mainly the pandemics like COVID-19 that are the persistent sustainability challenges resulting in destabilized freight operations and air travel leading to increased doubts regarding economic and environmental resilience. In view of these disruptions, a critical need arises for analytical methods that address the multi-scale and dynamic interactions impacting the environmental management and operational efficiency of transport system. While traditional linear econometric models are valuable for tracing long-term patterns, their efficacy carries limitations but while addressing the time-varying, multi-scale and transient co-movements rooted in this interdependent and complex system connecting the environmental outcomes with economic activity.

A research gap is yet to be filled in comprehensive analyses of the time-varying spectral coherence particularly integrating environmental-economic dimensions regardless of critical role of air-transportation sector among the Asian economies. While some prior studies methodically examine the sustainability relevant dynamic co-movements across countries for capturing time-varying relationships and multi-scale, whereas other highlights the particular elements of air-transport (e.g., economic impacts, passenger traffic, and freight) or individual countries. Panel data and conventional time-series models generally depend on the stable relationships across time and stationary assumptions which are impractical considering the exposure of sectors to environmental regulations, economic cycles, technological advancements, and unanticipated worldwide events. Furthermore, prior advanced studies overlooked the wider geopolitical trends and consequences of varying environmental and economic structures for co-movement patterns, while emphasizing particular bilateral relationships and narrow set of countries (Liu, et al., 2025; Longston et al., 2025). The aforementioned gap limits the comprehension of the ways air-transport systems of these economies align or differ across various time scales under the influence of external and internal environmental and economic factors. Thus, problem statement of the current study highlights the vital need for refined comprehension of interconnectedness of air-transport within Asia, especially concerning ecological and environmental linkages. The absence of detailed analysis determining the time-varying spectral coherence across the diverse economic landscape of Asia constraints investors, policymakers, industry stakeholders, and investors from formulating impactful policies for regional transport system, enhancing resource deployment, effectively evaluating systematic risks, and strengthening the economic sustainability and ecological robustness of the air-transport sector. Without such critical insight, sustainable growth, initiatives toward regional cooperation, sustained economic development might be challenged by the inefficiencies in the air-transport, leading to neglected opportunities for sustainable progress, ineffective collaborative progress and suboptimal resource utilization (Alonso, & Socorro, 2025; Ali et al., 2025).

This research endeavor to achieve the following objectives, in view of the outlined research gap and problem: i) to analyze and quantify the time-varying spectral coherence of air-transportation across different frequency bands and time scales over the course of the research timeline by demonstrating their role in environmental-economic interdependencies among Asian economies, ii) to investigate phase differences and lead-lag relationships in co-movements of air-transportation, demonstrating how transport sectors of these economies effect on each other's

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environmental governance and economic growth over short-, medium-, and long-term scales and iii) to contribute policy-relevant insights by interpreting multi-scale co-movement patterns of air-transport, enhancing sustainability-focused resilience strategies, infrastructure development and regional air-transport policy in emerging Asian economies.

In line with these objectives, the research formulates three central questions: i) How do the air-transportation sectors in Indonesia, India, Iran, Malaysia, Pakistan, Singapore, Sri Lanka, Turkey, Korea, and Japan shows time-varying spectral coherence at multiple time scales and frequencies, within the context of environmental-economic sustainability? ii) What are the observed time-varying phase relationships across different scales (leading, lagging, or in-phase) occur in Asian economies among their air-transportation sectors revealing about environmental and economic trends? iii) What are the implications of observed time-varying spectral co-movement patterns for investment strategies, stability-related insights, and regional air-transport policies in air-transport sector of Asia? Methodological diversity is often observed in prior research studies analyzing panel data and country-level time series. Traditional econometric analysis employ vector autoregression (VAR) models, cointegration analyses and panel regression models (fixed-effects, random-effects) which address temporal variation and cross-sectional while accounting for unobserved heterogeneity. VAR models assess causality and dynamic interactions across multiple series, in contrast to cointegration, which focuses on identifying the persistent equilibrium relationships. Nevertheless, these techniques often presuppose stationarity, and time-invariant relationships and linearity, which may be invalid for complex and highly dynamic sectors such as air-transportation, which experiences transient co-movements, sudden shifts in response to economic shocks and non-linarites, technological advancements and environmental policies at varying timescales. For instance, short-term disruptions (such as lockdowns) and medium term factors (such as recovery through vaccination) may produces the different impact on the air-transport and related environmental emissions throughout a global pandemic (Choi, et al., 2025; Arshad et al., 2025).

This study employs wavelet analysis as its primary methodology in order to mitigate these constraints and gaining a more nuanced perspective into complex dynamics of air-transport related to economic and environmental factors. The ability of wavelet analysis to simultaneously break down time series across both frequency and time domains makes it highly effective for investigating time-varying spectral coherence through multi-resolution analysis. This feature allows for separating short-term, high-frequency fluctuations (e.g., immediate shock responses) from long-term, low-frequency trends (e.g., gradual structural changes) within co-movements. Designed for non-stationary data typical in transport and economic statistics, this methodology reveals transient and localized patterns missed by regression methods or conventional Fourier transform. Wavelet coherence measures, specifically, phase alignment and strength of co-movements between time series of air-transportation of selected countries over both time and frequency. The technique highlights periods of strong synchronization and period of weak and no co-movement. Wavelet transform techniques have been applied in Medicine (Qassim, et al., 2013; Hassan, et al., 2010; Scholkmann & Dommer, 2012; Bellini, 2025; Parikh, et al., 2024; Carenzo, et al., 2025), astrophysics (Li, Gao & Zhan, 2009; Bloomfield, et al., 2004; Donner & Thiel, 2007; Kelly, et al., 2003), and geophysics (Liu, Hsu & Grafarend, 2005; Zamani, Samiee & Kirby, 2013; Aziz, et al., 2023; Grinsted, Moore & Jevrejeva, 2004; Shahid et al., 2025). Various wavelet variants—including CWT, WCOH, XWT, and WCA—facilitate detailed co-movement analyses between variable pairs or entities (Crowley & Mayes, 2009; Rua & Nunes, 2009). The phase data from wavelet coherence plays a key role in identifying whether one series leads or follows another, helping to uncover causal links and how shocks spread through the regional air-transport network, with important environmental and economic impacts. Recent research on COVID-19's effects on air-transport has effectively used wavelet analysis to uncover short-term (10–30 days) and medium-term (30–90 days) patterns of co-movement. These studies show how the pandemic's lockdown measures led to a decline in air traffic, which in turn influenced environmental emission trends. Additionally, the combination of wavelet analysis with neural networks has improved the ability to recognize and forecast air traffic patterns. This powerful and flexible approach provides detailed insights into changing spectral coherence over time, which is vital for managing the environmental and economic aspects of air-transportation sustainably, especially across the varied emerging economies in Asia. The rest of the paper is structured as follows: literature review, methodology, data collection, analysis, results and discussion, and conclusion.

LITERATURE REVIEW

Critical evaluation of contemporary studies is serious part of any research and is particularly crucial for researches employing advanced analytical techniques. Since the current research is focused on "times varying spectral

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coherence investigation of air-transportation of Asian emerging economies," with key emphasis on the variable 'air-transport, passengers carried', therefore, critical review of literature not only facilitates in developing a robust theoretical framework but also allows contextualizing previous findings and identification of knowledge gaps. Admittedly, there are many standalone reviews of contemporary literature viz (Papavasileiou, Papatheodorou, & Edmunds, 2025; Park, et al., 2025; Rossi, 2023; Mayer et al., 2024; Braithwaite, & Harrison, 2025 and Price, & Barnard, 2025; Ali et al., 2025; Khalid & Abdul, 2025) but they do not suffice to set the exact context of the current study. Furthermore, it provides a foundation to ground the research in earlier methodological and empirical advancements and a justification for selection of wavelet-based techniques over traditional methods for analyzing multiscale, non-stationary complex time series data. Targeted keywords were used while literature search including "time-frequency analysis in transportation", "Asian air-transport dynamics," "air-passenger time series," "spectral analysis in air-transportation," "wavelet coherence," "air-transport passengers," etc. Reputable academic databases like JSTOR, Elsevier's (ScienceDirect), Emerald Insight, Springer Link, Taylor & Francis Online, Wiley Online Library etc. were explored systematically to ensure comprehensive coverage of contemporary studies spanning methodological, empirical and theoretical research pertaining to air-transportation. Globally, the air-transport, particularly air-passenger movement is documented as a prime driver of development, economic connectivity, and globalization. Alongside, it is also widely recognized as a growing source of many environmental concerns including noise pollution and carbon emissions (Luna & Luna, 2018; Wang et al., 2025; Weng, et al., 2025).

Mutascu & Sokic (2023) and Drew & Sheth (2015) demonstrate strong connection between air-passenger volumes and policy environments, technological progress and macroeconomic variables thus emphasizing that environmental management be incorporated within aviation growth frameworks. In view of inherently multiscale and non-stationary behavior of air-transport data, wavelet analysis has been adopted to interpret it. Mutascu and Sokic (2023), focused on examining the impact of COVID-19 pandemic on air-transportation specifically in context of Europe, employed wavelet coherence technique and revealed wavering co-movement intensities across various time-frequency bands and relative environmental effects during travel restrictions like reduction in emissions. The strength of wavelet coherence over time domain and Fourier analysis is highlighted in these studies particularly in identifying transient dependencies and localized oscillations. Moreover, a wavelet transform-based framework was developed in study conducted by Zhang et al., (2023) for prediction of flight trajectories. This highlighted the utilization of wavelet approaches owing to the power of time-frequency methods for covering complex temporal features of flight data and potential application in the industry for optimization of flight paths for reduced emissions and fuel efficiency (Luna & Luna, 2018; Wandelt et al., 2025). Likewise, the wavelet transforms were also employed by Modzelewski and Lichota (2025) in their study focused on analyzing aircraft motion that further established the applicability of wavelet technique from both analytical and operational perspective particularly in the aviation research, with indirect contribution in environmental performance improvements as an added advantage. The methodological rational of employing wavelet techniques was further solidified by the work of Drew and Sheth's (2015) focusing on classification of air traffic behavior. This also highlighted that globally, the air-passenger data is multiscale in nature and this fact is significant for comprehending environmental-economic trade-offs. For air-passenger transport studies, Asian markets particularly present a fast growing and vibrant context when examined from bloc and regional level perspective. In context of Asia, passenger air-transport is closely tied with broader environmental and economic indicators owing to regional integration efforts, infrastructure development and regions rapid economic growth (Bassem, 2025; Hanvoravongchai & Paweenawat, 2025).

Studies, that employed wavelet coherence, have effectively shed light on co-evolution of air-passenger volumes with environmental variables, GDP and trade flows in context of Asian countries. Wavelet-based methods are employed to analyze volatility of air-passenger demand in ASEAN states revealing the divergence patterns and dynamic synchronization reliant on environmental regulation implementation, policy changes and economic cycles (Hussain & Khan, 2022; Marc, 2024; Anuar, et al., 2025; Ito & Zhang, 2025). In context of emerging Asian markets, further evidence of frequency-specific co-movements was provided by study conducted by Altuntas and Baykasoğlu (2020) that found time-varying and nonlinear correlations among passenger transport and ecological and economic drivers. The key focus of this research was air-passenger movement in context of Korea relative to various transport modes particularly shipping. The finding of the study indicated distinct multiscale relations emphasizing balance between environmental considerations and broader economic integration processes. The

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results of these studies clearly established the suitability of wavelet coherence analysis in determining the complex frequency and temporal interactions of air-passenger transport with sustainability implications in Asian economic blocs. However, considerable heterogeneity emerges at the country level owing to variances in geopolitical factors, environmental standards, infrastructure investments and policies effecting passengers flows. In the countries like Indonesia, Japan, and India, liberalization reforms and infrastructural expansion resulted in significant impact over volume of air-passenger as well as environmental footprints (Mustapha, 2022; Leelaworas et al., 2025; Rizwan & Iqbal, 2025).

Likewise, the case of Pakistan also carries noticeable significance owing to its developmental challenges, strategic location and rising focus on harmonizing economic growth with ecological management. Air-passenger transport dynamics in context of Pakistan have been examined by utilizing wavelet coherence in relation to its neighboring countries, environmental and economic factors, revealing coherence fluctuations, possibly driven by environmental, infrastructural and political conditions, and crucial periods of lead-lag relationships. Overall, the findings of the research studies focused on the country level emphasizes the need employ flexible methods capturing changing coherence over environmental impacts and economic contexts in order to analyze air-passenger data. The study conducted by Fareed, et al. (2023) focused on global perspective on air-passenger demand. The countries studied in the research conducted by (Achy & Lakhnati, 2019; Weber, 2022; Nguyen, 2023, Çelik et al., 2025; Franciscone et al., 2024; Ahmad & Hu, 2025) with wavelet and other related/time-frequency techniques included Japan, Korea, Turkey, Sirilanka, Singapore, Malaysia and Iran which revealed various spectral patterns associated with varying environmental policies, technological advancement levels, trade intensities and economic structures. Silva & Sampaio (2012) found that wavelet coherence assists in the identification of delayed causalities, phase differences and transient synchronization. Particularly demand analysis and airport traffic forecasting is benefited from these techniques owing to their ability to incorporate environmental variables and multi-resolution capabilities variables (Zhang & Duan, 2017; Suzuki & Kobayashi, 2014; Ahmad, 2018; Jaelani & Nazara, 2022; Chaudhary & Ahmad, 2023).

The critical review of literature accentuates the significance and accuracy of application of wavelet coherence analysis to air-transport passenger data and establishes its significance as a precise tool to be employed for analysis of non-stationary time-series data exhibiting regime shifts, shocks and multi frequency oscillations. The limitations of traditional linear models like inadequacy in capturing the structural breaks and evolving dynamics such as sudden shocks like policy shifts and pandemics make these less effective in studies focusing on air-transport data. Mutascu & Sokic (2016) demonstrated that wavelet analysis can uncover time-specific relationships in regional air-passenger flows, strengthening theoretical models related to connectivity of networks, sustainability science and complex systems dynamics. For example, research conducted in Turkey by Çelik et al. (2024) demonstrated that heteroscedasticity of passenger volumes and seasonal shifts using weighting wavelet transforms, yielding stronger forecasts that could help in optimizing schedules to reduce emissions. Moreover, illustrating the versatility of wavelets, Bai and Wei (2015) introduced the integrating wavelet decomposition with grey models and exponential smoothing highlighting wavelet tools in handling non-stationary series critical to environmental-economic decision-making. Collectively, this body of work underpins the current investigation's focus on wavelet analysis and spectral coherence to investigate time-scale dependent relationships and co-movements in air-passenger data in emerging Asian economies, particularly in relation to environmental considerations. The body of literature focused on air-passenger transport in Asian emerging economies revealing multifaceted and comprehensive discourse incorporating behavioral dimensions, policy, operational, environmental and economic factors. International research evidences indicate that air-passenger mobility is strongly linked to economic performance. Profillidis and Botzoris (2015) documented that in 53 countries, correlation between per capita GDP and the number of air trips per inhabitant, reflecting aviation's capacity to stimulate economies but also its environmental trade-offs. Additionally, the study by Zhang and Findlay (2014) demonstrated that policy liberalization in air-transport markets marked influence on international passenger flows, whereas, restrictive aviation regimes suppress such flows across global cities, thereby shaping patterns of related environmental outcomes and international connectivity (William & Adam, 2018; Emodi, 2019; Ibrahim & Simian, 2023; He, et al., 2025). At the macro-level, such observations provide a backdrop for understanding distinct growth paths of emerging Asian economies, many of which are characterized by ongoing liberalization efforts with mixed results and operating under diverse environmental regulatory frameworks.

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The literature within the broader regulatory environment and market structure highlights that divergent and competing interests of airlines and their customers can shape ecological outcomes. Research by Kistler et al., (2018) established that passengers depend on airlines to represent their needs, however, airline and passengers' relationship is marked by the gap between expectations and priorities wherein airlines prioritize operational efficiency than passenger convenience and investment in sustainable infrastructure (Ali et al., 2022; Calin & Hordonic, 2023; Bassem, 2025). Socorro and Betancor (2020) highlight that competitive market challenges in air-transport sector is further complicated by the presences of dominant incumbent airlines, whose capacity to cross-subsidize certain routes and entrenched market positions hinder new entrants like Air Europa Express, which ultimately could not sustain operations (Ashiq et al., 2023; Cristea et al., 2025). The findings reveal how competitive asymmetries shapes air-transport markets of emerging Asian economies and signal the need for regulatory actions to improve service quality, incentivize environmentally sustainable practices and foster equitable competition. The expansion of air-passenger transport has emphasized the environmental sustainability as a central concern, with concentrated research on the carbon reduction techniques (Xu et al., 2025; Salhi et al., 2025; Marc et al., 2026). The effectiveness of cap-and-trade mechanisms were established as a policymaker tool for harmonizing sustainability objectives and economic incentives in effectively controlling emission in air-passenger transport (Xu et al., 2016; Gillani et al., 2026). Through computational modeling, Qiu et al., (2017) strengthened the evidence by demonstrating the mixed carbon allowance allocation mechanisms that can facilitate better emissions reduction and encourage institutional implementations. Qiu et al. (2020) emphasized the significance of carbon tax incentive policies, while advocating for balanced regulatory frameworks that combines airlines operational strategies and financial incentives to improve fuel consumption and emission performance in the airline sector by complementing these policy-centered approaches. From an operational perspective, Lo et al. (2020) suggested that greater aircraft size on selected routes mitigates per-passenger environmental effect, emphasizing fleet optimization as an effective emissions reduction strategy, especially pertinent to the Asia's diverse aircraft fleet modernization efforts. Another important research dimension which has direct effects on economic and environmental sustainability of the air-transport networks of Asian region focused on network vulnerability and infrastructure resilience. Findings by Voltes-Dorta et al., (2017) indicated a need for strategic operational policies to reduce environmental risks and improve network resilience by revealing that traffic distribution and alliance structures influences passenger delays and airport criticality. The vulnerabilities highlighted by the COVID-19 pandemic are illustrated by the Warnock-Smith et al. (2021), demonstrating that routes operated by financially resilient carriers in regions with lower infection rates experienced faster recovery and limiting long-term environmental inefficiencies. Given the diverse pandemic effects across emerging Asian economies, this evidence emphasized that resilience factors such as network design, governmental restrictions and airline financing are vital in determining recovery paths with environmental and economic consequences.

Scholars examining the passenger perspective, emphasized the significance of satisfaction factors and heterogeneous consumer preferences in shaping competitive positioning, promoting sustainable travel and expanding markets. Using ordered logit models, Bellizzi et al. (2018) established that passenger satisfaction varies by service attributes and demographic groups, stressing the requirement for airlines to customize marketing and services to enhance traveler satisfaction and incentivize environmentally responsible behaviors. According to Román and Martín (2014), the effective intermodal integration between air and high-speed rail services through smoother modal transfers and better schedule alignment increases payment willingness and passenger utility, reflecting a shift in mobility landscape in Asia's multimodal transport ecosystem and their associated environmental advantages (Oesingmann, & Ennen, 2025; Wang et al., 2025; Audi et al., 2025). Lee, Kim, and Sim (2019) established that lower fares motivated younger and more frequent travelers to accept remotely piloted passenger aircraft whereas conventional piloted flights are preferred by risk-averse passengers emphasizing the need to design environmentally focused service and public acceptance strategies (Ali & Audi, 2016; Fondevila-Gascón, et al., 2025). The landscape becomes more complicated due to policy instruments and social equity issues such as subsidies. Valido et al. (2014) developed a theoretical model that proposed analyzing passenger subsidies in Europe, showing how they safeguard outermost region for equity purpose while also acknowledging unintended market effects when carriers exercise power.

In Asian emerging economies, trade-off between environmental impact, efficiency, and equity is being resonated while many struggling with regional disparities and a prerequisite to preserve ecosystem health and market competition alongside ensuring accessible air-transport. Settey and Gnap (2020) conducted a comparative analysis

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of international bus transport versus air-transport, finding that air-transport over long distance excels in enhancing passenger quality and reducing transport time despite environmental concerns, particularly relevant to Asia's vast and diversified geography and economic frameworks, emphasizing the need for balanced policy approaches. Effective methodologies for dependable forecasting represented a key focus in inquiry essential to strategic transport planning and environmental management. The advanced direct demand models established by Gelhausen, Berster, and Wilken (2018) incorporating origin-destination flows, flight types, and trip purposes, increasing forecast accuracy for passenger volumes that is essential for policy formulation, infrastructure planning and resource allocation in environmentally sensitive and dynamic markets (Bassem, 2025). Integrating forecasting methods within time-frequency analytical technique such as wavelet-based spectral coherence analysis, as utilized in this research, facilitates the detection of underlying, economic indicators, environmental variables, changing relationships among air-passenger volumes and policy interventions across multiple time horizons, providing an advanced powerful method to investigate complex temporal behavior of air-transport sectors in emerging Asian economies.

Synthesizing these themes, the existing studies emphasized the value of applying time-varying analytical methods to capture the evolving and multifactorial relationships between environmental stainability, air-transport passenger trends, and economic expansion. World Development Indicators comprehensively defined the variable 'air-transport, passengers carried,' which covers all international and domestic passengers on registered carriers with in a country, ensures this study adheres comparability and global benchmarks. Evidence from the literature emphasizes the need for temporally sensitive, comprehensive and nuanced approaches to address issues in air-transport including resilience to shocks, competitive dynamics, environmental sustainability, social equity, passenger preferences and emission control (Oliveira, Couto, & Pimentel, 2025; Nerja, & Sánchez, 2025). Spectral coherence methods and wavelet analysis are especially appropriate for detecting cyclical behavior, co-movements across time and frequency scales, encompassing those impacting economic and environmental phenomena. Summarizing, this literature review consolidates methodological contributions and empirical work to underpin the use of wavelet coherence as an effective tool in examining temporal and spectral relationships in air-transport passenger data. The literature review offers a well-grounded basis for this study, from global level wavelet methods for examining pandemic impacts and predict flights trajectory to Asian regional studies of environmental synchronization, trade, transport, and Pakistan-focused country level examination on air-passenger dynamics. The problem-oriented literature on spectral coherence and wavelet-based forecasting highlights effectiveness of wavelet analysis in dealing with multi-scale, non-stationary nature of air-passenger time series data and providing analytical and theoretical framework of this study from a management viewpoint and environmental economics.

METHODOLOGY

This study is moored in a positivist philosophy, emphasizing objective measurement and analysis of quantitative data to uncover generalizable patterns in air-transport passenger volumes and their environmental-economic linkages across Asian emerging economies. The research espouses a deductive approach, starting from the theoretical premise that spectral coherence in air-passenger transport time series among countries varies over time and frequency, reflecting both economic dynamics and associated environmental impacts. This leads to an empirical examination using advanced signal-processing methods—in particular, wavelet coherence analysis—to test and explore these relationships within a panel dataset. The overall research design is quantitative and longitudinal, employing a country-level panel data analysis encompassing ten Asian countries viz Indonesia, India, Iran, Malaysia, Pakistan, Singapore, Sri Lanka, Turkey, Korea and Japan, over a sixty-year period.

The design assimilates literature review, systematic data accumulation from authoritative sources, and comprehensive time-frequency analysis to capture both economic and environmental temporal patterns. The population under study comprises of Asian emerging economies with available data on air-passenger volume and implicitly their environmental footprints on the World Development Indicators (WDI) database. The sampling frame is purposive and exhaustive, incorporating all countries meeting the inclusion criterion of having continuous and consistent data on the variable 'air-transport, passengers carried' for the full time span of the last sixty years (1960–2019). Thus, the sample design is a census of available countries fitting data availability criteria, enhancing representativeness and external validity in assessing environmental and economic sustainability. The sample size includes ten countries, ensuring broad geographic, developmental, and environmental heterogeneity while balancing data completeness and comparability. Data collection is secondary and archival, drawn entirely from the WDI website managed by the World Bank, which provides standardized and internationally comparable annual

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data on air-transport passenger numbers, defined operationally as "air-passengers carried" — including both domestic and international passengers of all air carriers registered in the country. This definition ensures consistency across countries and time per WDI methodological standards, allowing inference on associated environmental impacts linked to passenger volumes.

The dataset was rigorously screened for completeness, quality, and periodicity prior to analysis. The core technique of data analysis is wavelet analysis, a powerful methodology for examining non-stationary time series data in both the time and frequency domains simultaneously (Mutascu & Sokic, 2023; Drew & Sheth, 2015). Wavelet analysis overcomes limitations posed by classical statistical methods that assume stationarity or homogeneity over time, thereby enabling detection of localized transient phenomena, periodicities, scale-dependent co-movements, and implicitly their environmental-economic correlations. The analytical scheme proceeds in several phases: first, descriptive statistical analysis to summarize primary characteristics and trends of passenger transport time series alongside environmental relevance; second, construction of time-series graphs for visual pattern identification; third, application of wavelet power spectra to individual countries to identify dominant scales, temporal oscillations, and environmental implication windows; fourth, cross-wavelet power spectra analyzing bivariate interactions between Pakistan and other countries to explore inter-country transport linkage intensities and potential shared environmental impacts; and fifth, wavelet coherence analysis quantifying time-frequency localized co-movement strength and phase relationships specifically contrasting Pakistan with each of the other emerging economies (Mutascu & Sokic, 2023; Drew & Sheth, 2015; Modzelewski & Lichota, 2025). The Morlet wavelet has been selected as the 'mother wavelet' due to its optimal balance between time and frequency localization, proven effective in air-transport and other economic time-series analyses (Mutascu & Sokic, 2023; Drew & Sheth, 2015).

This allows decomposition of time series data into coefficients representing various time-scale frequencies while preserving temporal heterogeneity and environmental relevance. This multi-resolution approach facilitates isolating short-term shocks (e.g., policy changes, crises, environmental regulations) and long-term cyclical behaviors relevant to air-passenger dynamics and their environmental-economic interplay in emerging Asian economies. The justification of the methodology relies on the intrinsic characteristics of the data and research questions. Air-transport passenger data are typically non-stationary, susceptible to structural breaks and nonlinear fluctuations given geopolitical upheavals, economic transformations, regulatory reforms, environmental policies, and external shocks such as pandemics and technological changes (Mutascu & Sokic, 2023; Bai & Wei, 2015). Traditional econometric methods such as co-integration or autoregressive models impose strict assumptions limiting their applicability to such data. Wavelet coherence analysis uniquely accommodates these data properties, offering simultaneous localization in time and frequency domains, vital for uncovering evolving interdependencies between countries that include environmental and economic dimensions (Drew & Sheth, 2015). Further, wavelet analysis enhances interpretability of co-movements across multiple scales, critical in capturing both seasonal patterns and multi-decadal trends, thus enabling policymakers and stakeholders to grasp the dynamic synchronization or divergence of air-transport sectors and related environmental outcomes across Asia (Modzelewski & Lichota, 2025).

DATA, ANALYSIS, RESULTS & DISCUSSION

This part of the study comprises of data-collection, basic expressive (descriptive) statistics and inferential investigation, enlightenment upon the results of descriptive and inferential investigation and the discussion qua actualities. The data of the variable i.e. "air-transport, passengers carried" are acquired from the World Development Indicators' website (WDI, 2021). The variable is defined as "air-passengers carried include both domestic and international aircraft passengers of all air carriers registered in the country". The time series from January 1, 1970 to December 31, 2019 is used for analysis (Table 1). The time span and the countries subject to analysis are chosen on the basis of availability of the data.

Data obtained from WDI is in annual number of air-passengers carried (both domestic and international) of all air-carriers registered in the country concerned. The authors transformed this data in to weekly figures through some functions of MatLab in order to obtain more detailed frequency-time resolution through wavelet analysis. Hence, the weekly descriptive statistics of the 'air-passengers carried' as used in this study for wavelet analysis is presented in Table 2. Analysis of the data has two parts i.e. descriptive-statistical analysis (Table 2) and inferential-mathematical (wavelet) analysis Figures 1 to 4 below.

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Air-transport, passengers carried (WDI, 2021)

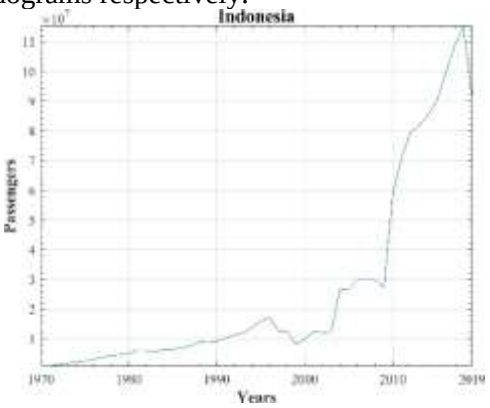
Year	Indonesia	India	Iran	Malaysia	Pakistan	Singapore	Sri Lanka	Turkey	Korea, Rep.	Japan
1970	826,400	2,671,600	715,600	748,900	1,335,900	748,900	104,600	1,035,700	1,208,100	16,315,100
1971	994,500	2,554,000	761,400	875,100	1,085,600	875,100	116,000	1,476,000	1,463,600	17,880,500
1972	1,286,800	3,285,800	894,800	1,015,600	625,200	976,100	116,000	1,774,500	1,640,000	20,169,500
…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…
1994	13,924,500	11,518,400	5,803,500	14,249,800	5,663,700	9,929,400	1,066,800	6,871,600	24,932,300	83,913,504
1995	15,977,200	14,260,600	6,290,600	15,417,800	5,342,600	10,779,300	1,155,700	7,749,000	29,345,200	91,797,000
…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…
2017	108,393,123	139,752,424	26,858,179	58,711,937	7,260,769	38,094,990	5,403,577	107,917,326	82,818,983	123,898,000
2018	115,154,101	164,035,638	23,029,380	60,481,772	6,880,637	40,401,515	5,882,376	115,595,496	88,157,579	126,387,527
2019	91,323,153	167,499,116	21,641,449	63,623,130	7,420,378	43,050,722	5,582,446	111,028,629	92,434,079	130,233,352

Table 2: Descriptive Statistics based on Transformed Data

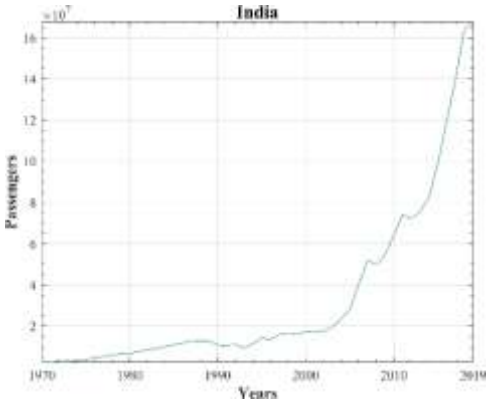
Description	Indonesia	India	Iran	Malaysia	Pakistan	Singapore	Sri Lanka	Turkey	Korea, Rep.	Japan
Mean	25,910,277	31,981,762	8,783,163	17,858,129	4,814,473	13,637,191	1,780,753	22,216,021	26,101,741	77,194,741
Standard Error	239,409	296,071	48,955	125,814	15,583	84,792	12,739	243,683	172,540	239,732
Median	11,351,679	12,889,500	6,047,050	14,131,022	5,285,813	10,354,350	1,111,250	7,310,300	27,119,960	87,343,438
Standard Dev.	32,028,908	39,609,404	6,549,317	16,831,854	2,084,774	11,343,746	1,704,266	32,600,798	23,082,934	32,072,143
Kurtosis	0.8728	2.7858	-0.5760	0.5614	-0.4534	-0.2493	-0.2395	1.6414	0.5908	-1.2045
Skewness	1.5291	1.8737	0.6661	1.2839	-0.1748	0.8873	1.0039	1.7458	1.0204	-0.3611
Range	114,327,70	164,945,116	26,142,579	62,874,230	9,003,154	42,301,822	5,782,376	114,559,796	91,225,979	113,918,252
Minimum	826,400	2,554,000	715,600	748,900	625,200	748,900	100,000	1,035,700	1,208,100	16,315,100
Maximum	115,154,10	67,499,116	26,858,179	63,623,130	9,628,354	43,050,722	5,882,376	115,595,496	92,434,079	130,233,352
Sum	463,742,135,668	572,409,583,494	157,201,059,262	319,624,789,406	86,169,429,583	244,078,441,422	31,871,909,011	397,622,340,362	467,168,968,501	1,381,631,468,565
Count	17,898	17,898	17,898	17,898	17,898	17,898	17,898	17,898	17,898	17,898

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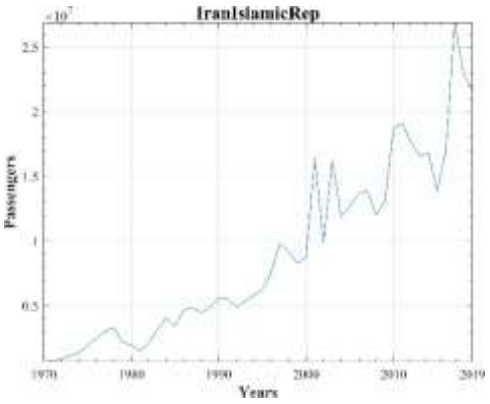
Table-2 portrays the descriptive breakdown of variables. It displays mean, standard error, median, standard deviation, kurtosis, skewness, range, minimum, maximum, sum, and the count of number of air-passengers carried by the registered air-carriers of every country under study. Wavelet analysis (Figures 1 to 4) below is a mathematical function that offers modeling base for nonstationary time series data. It offers info about time, location, and frequency by: i) stretching, ii) squeezing, and iii) shifting. This method is used to identify and analyze: i) discontinuities, ii) patterns, iii) sharp spikes, iv) de-noising, and v) statistical estimation/prediction from economic time-series. Step by step mathematical process is applied to the data which includes: i) choosing mother wavelet, ii) multi-resolution analysis, iii) decomposition, iv) down-sampling, v) up-sampling, vi) filtering, and vii) summation. Frequency is divided into frequency-bands i.e. high-pass filter bands (the coarser or approximation of coefficients) and low-pass filters (detailed/precise approximation of coefficients). Wavelet inherently is a visual representation analysis of time-series. It is mathematical process of integration & differentiation performed on MatLab software that gives set of plots and wavelet periodograms. The times series' plots of air-passenger carried by the registered air-carriers of every country are mentioned in Figure-1, wavelet-power-spectra of air-passengers carried by registered carriers of every country (i.e. continuous wavelet transform) is given in Figure-2, cross-wavelet-transform spectra of air-passengers of every country in contrast to that of Pakistan is given in Figure-3 and wavelet-coherence-spectra of air-passengers of every country with contrast to Pakistan is given Figure-4 The plots & spectra are inspected carefully by the authors for detecting: i) horizontal and/or vertical patterns, ii) sharp peaks, iii) defuse areas, and iv) other significant or non-significant events (if any). Step-wise scheme of wavelet-analysis, mathematical algorithm, definitions and symbols are adopted from Aziz et al. 2023 and not reported here for the sake of brevity. Findings, of the inspection of spectra by authors, are mentioned below the every set of periodograms respectively.



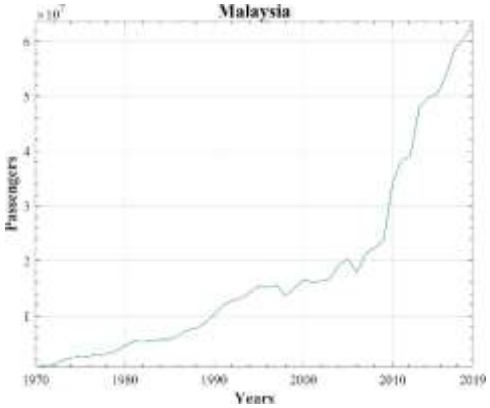
1(a)



1(b)

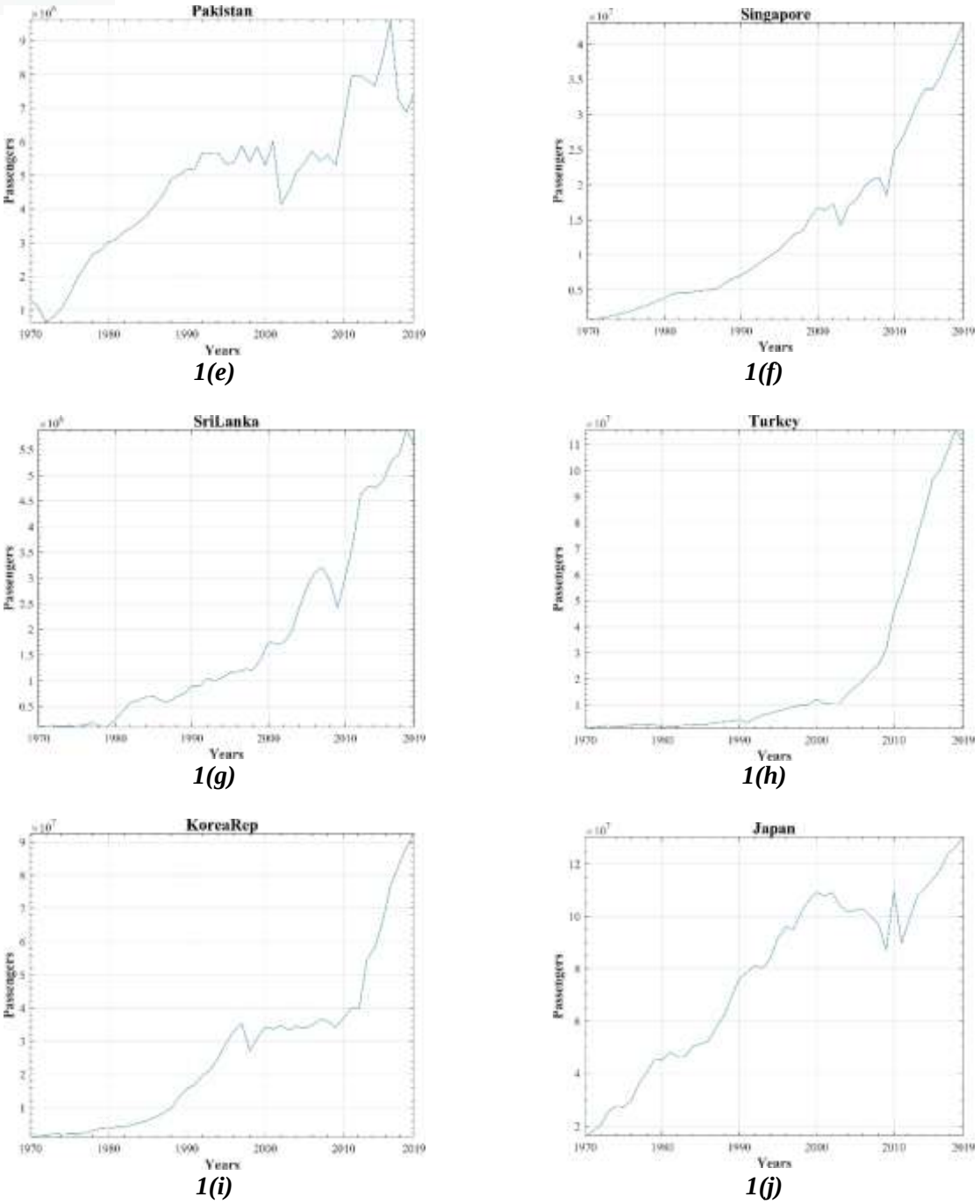


1(c)



1(d)

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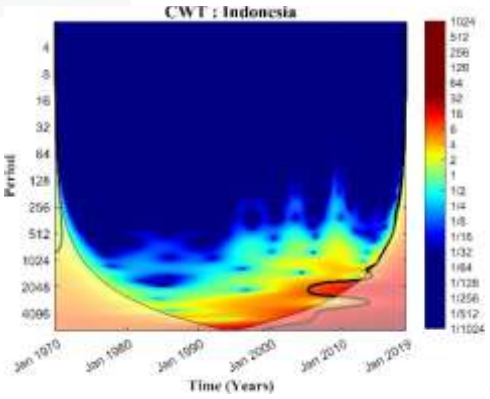
1(e) *1(f)* *1(g)* *1(h)* *1(i)* *1(j)*

Figure-1: Plots of Time Series of Air-Passengers Carried by the Registered Air-Carries of Countries Understudy 1(a)-1(j)

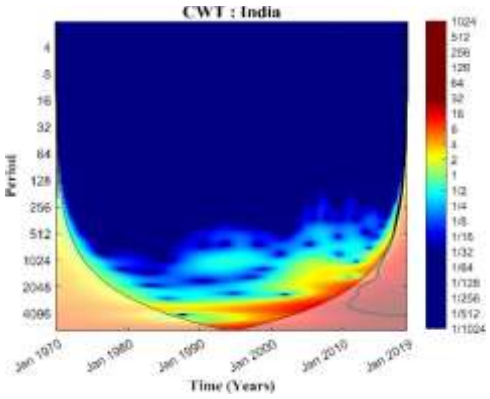
Plots are created using wavelet tool box of MatLab where the number of air-passengers are represented on Y-axis and weeks/years are displayed on X-axis. Variation in air-passengers over the period of time can be visually observed on respective plots.

After the representation of time series data of air-passengers on plots, the periodograms of air-passengers' time-series are generated by applying the continuous wavelet transform (Figure 2).

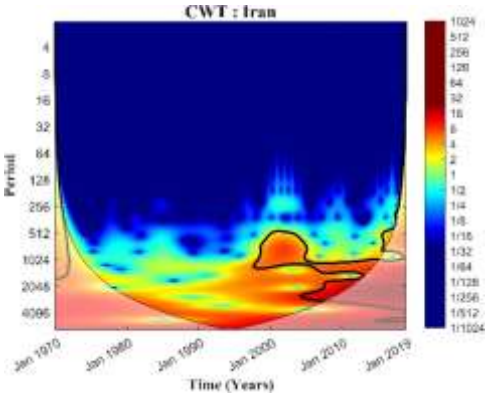
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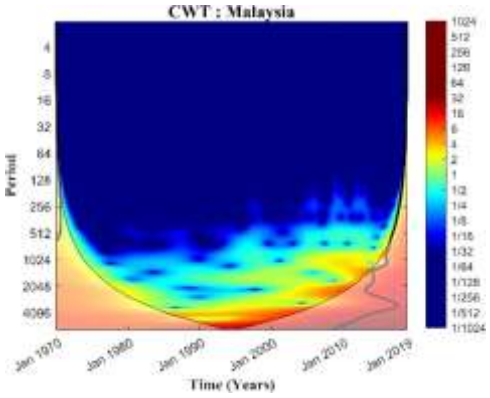
2(a)



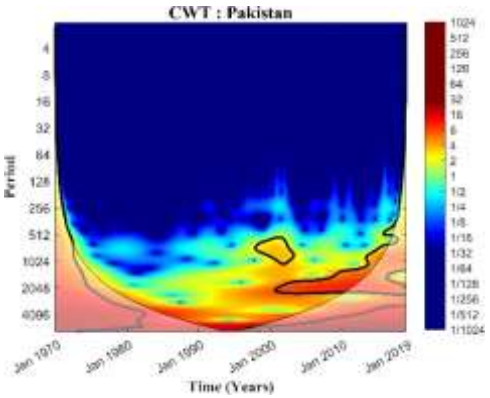
2(b)



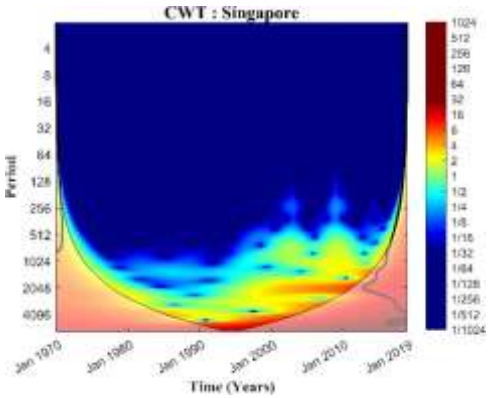
2(c)



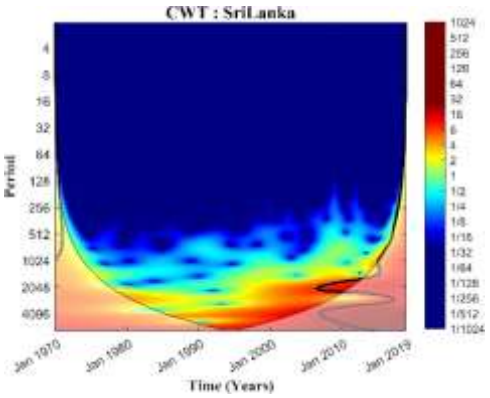
2(d)

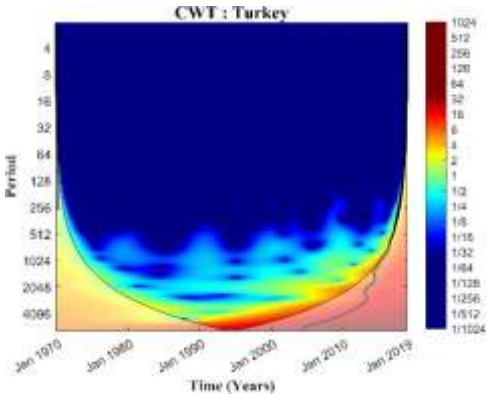


2(e)



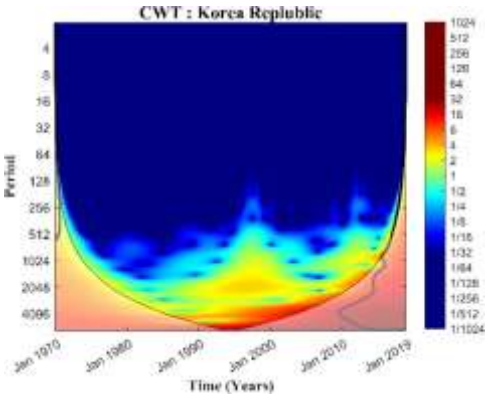
2(f)



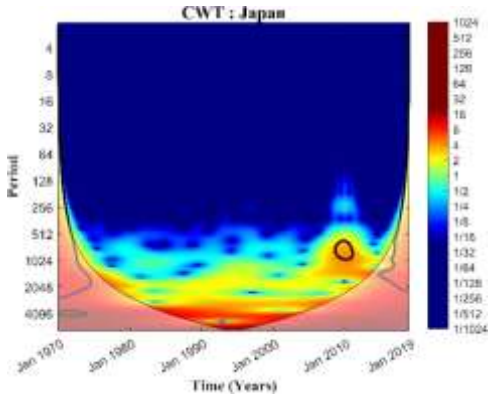


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2(g)



2(h)



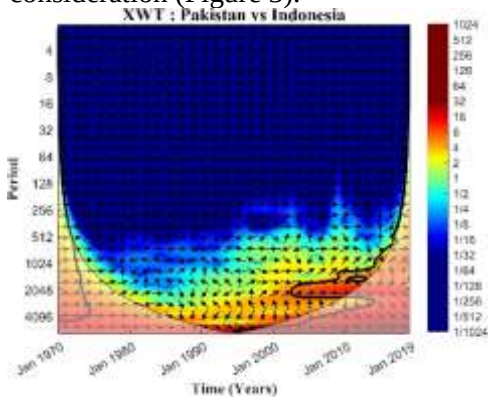
2(i)

2(j)

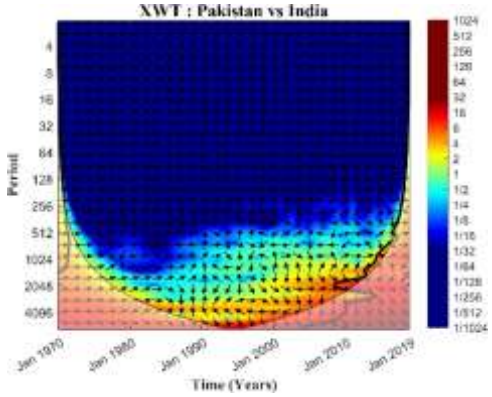
Figure-2: Individual Wavelet Power Spectra

Periodograms air-passengers carried by the registered air carriers of the countries under study i.e. 2(a)-2(j), where the time is represented on the horizontal-axis and scale inversely related to frequency is represented on vertical-axis. Color-scale characterizes wavelet coefficients' magnitude from blue to red (i.e. blue the coarser coefficients and red the detailed coefficients). Brighter regions in periodogram specify presence of significant signal-components at detailed times and scales. Curved thick black line is known as Cone of Influence (COI), a bit shaded area shows 5% confidence level and edge-effects.

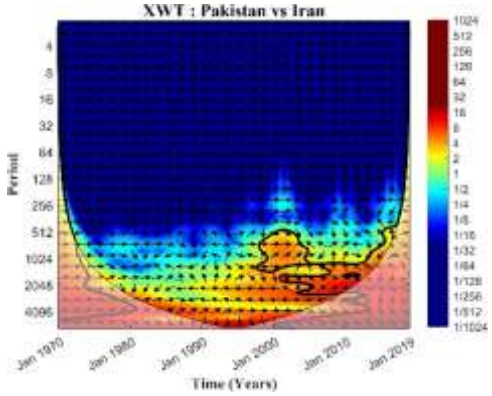
After the individual wavelet power spectra of air-passengers carried by the registered carriers of countries under investigation, the study moves on to cross wavelet transform (XWT) spectra for that of each country for time period under consideration (Figure 3).

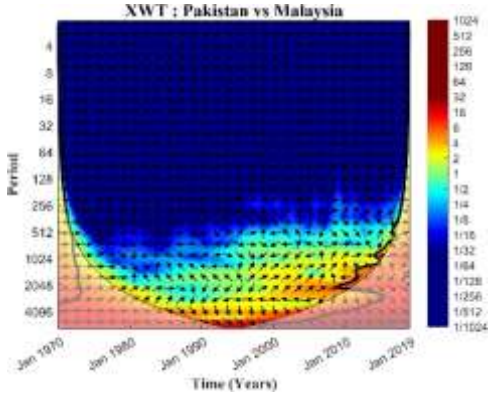


3(a)



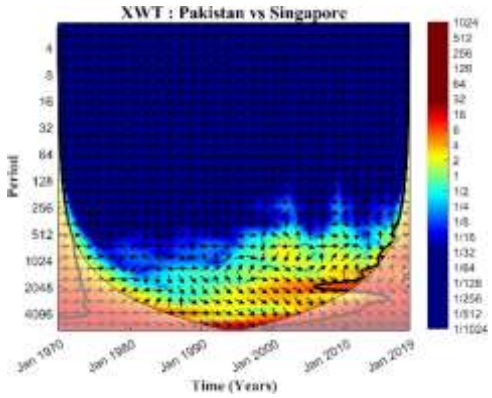
3(b)



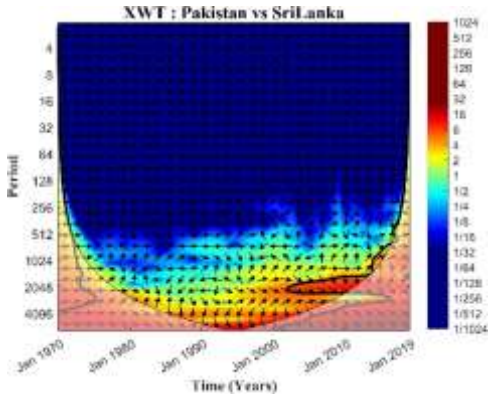


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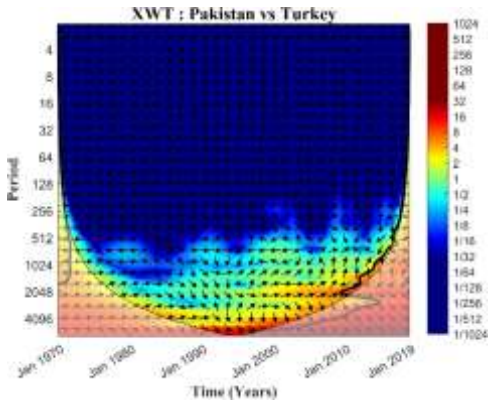
3(c)



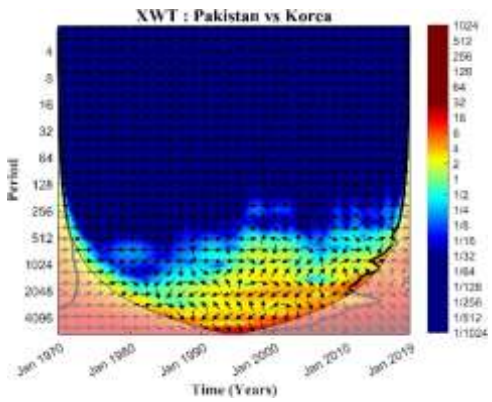
3(d)



3(e)

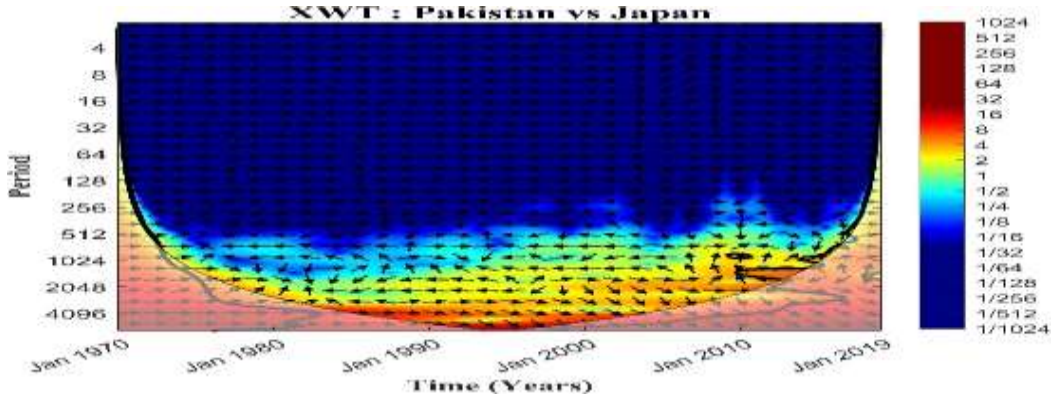


3(f)



3(g)

3(h)



3(i)

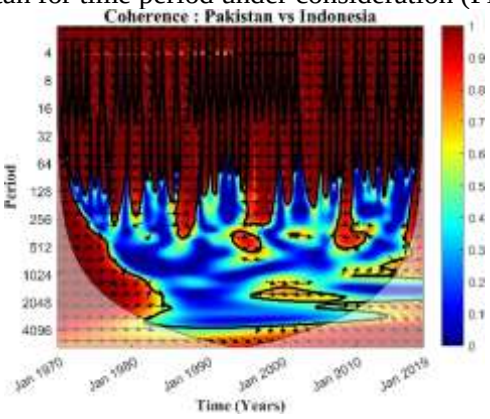
Figure-3: Periodograms of Cross Wavelet Transform (XWT) 3(a) to 3(i)

In periodograms air-passengers 3(a) to 3(i), the time is represented on the horizontal-axis and scale inversely related to frequency is represented on vertical-axis. Color-scale characterizes wavelet coefficients' magnitude from blue to red (i.e. blue the coarser coefficients and red the detailed coefficients). Brighter regions in periodogram specify presence of significant signal-components at detailed times and scales. Curved thick black line is known as Cone of Influence (COI), a bit shaded area shows 5% confidence level and edge-effects. Thick black arrows capture contrasting co-variance of air-passengers carried by the carrier of one country with that of the other and the phase information is captured by direction of the arrows i.e. exact-right arrows show that air-passengers carried

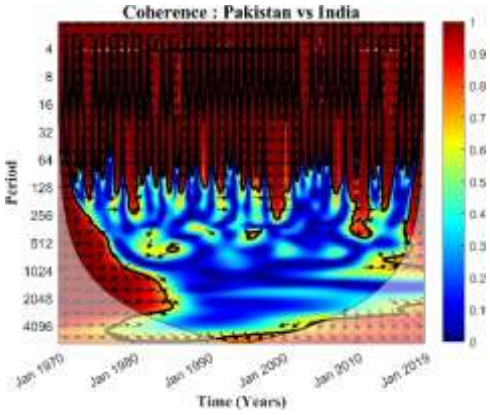
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time-series of country-x and that of country-y are positively correlated, exact-left arrows show that x and y are negatively correlated, up-right arrows show that x and y are positively correlated and x is leading, whereas, y is lagging, down-right arrows show that x and y are positively correlated x is lagging and y is leading, up-left arrows show that x and y are negatively correlated x is lagging, and down-left arrows show that x and y are negatively correlated x is leading.

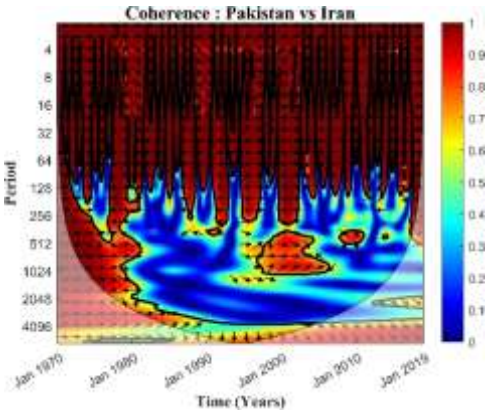
After cross wavelet transform (XWT) spectra contrasting for that of each country for time period under consideration, the study moves on to wavelet coherence transform spectra contrasting each country against Pakistan for time period under consideration (Figure 4).



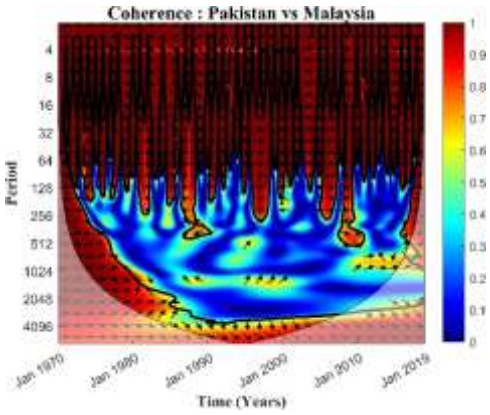
4(a)



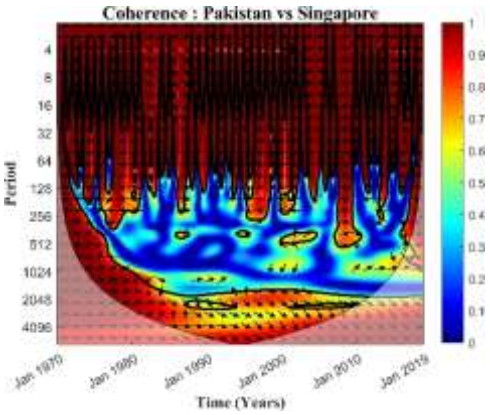
4(b)



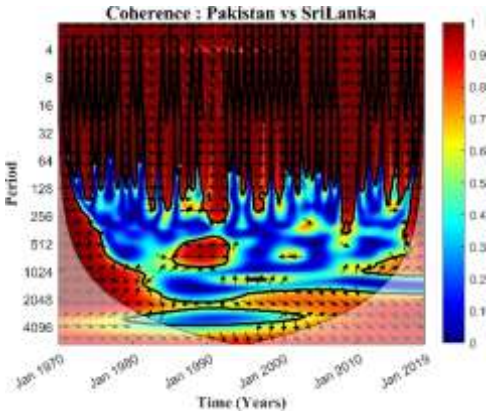
4(c)



4(d)

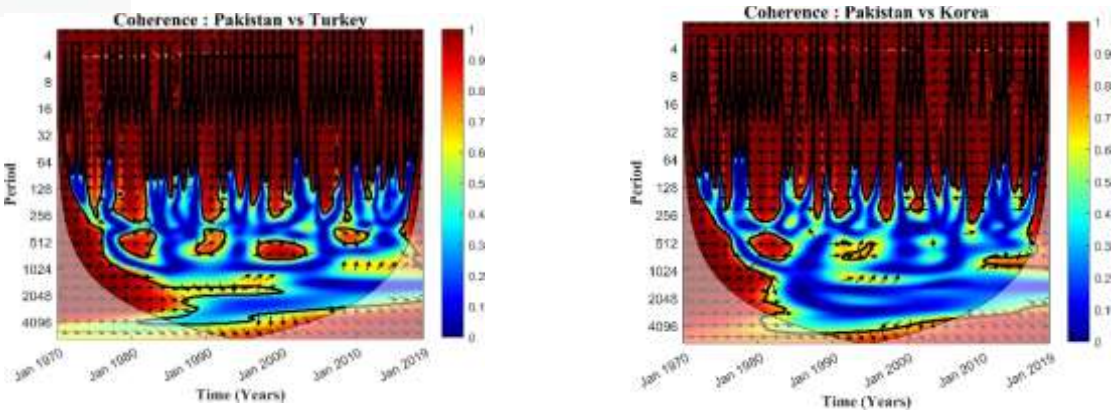


4(e)



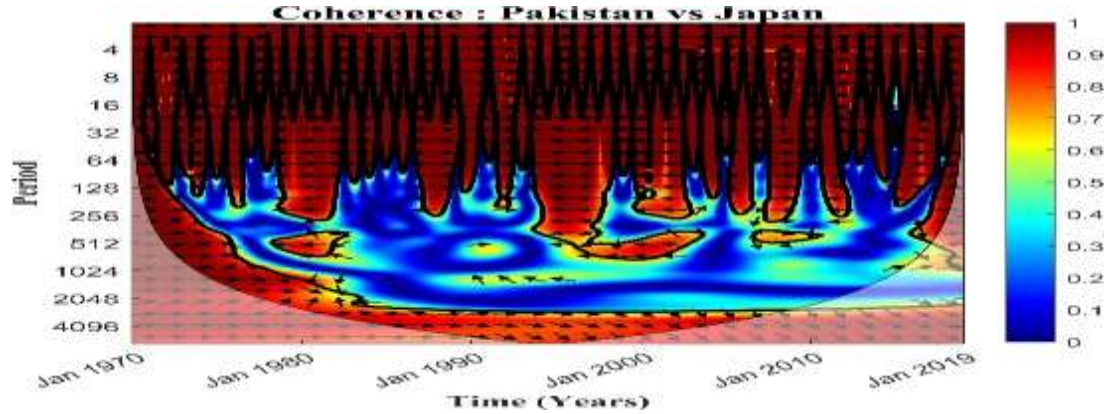
4(f)

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4(g)

4(h)



4(i)

Figure-4: Periodograms of Wavelet Coherence Transform 4(a) to 4(i)

In periodograms of air-passengers carried by the registered carriers of the countries under study 4(a) to 4(i), the time is represented on the horizontal-axis and scale inversely related to frequency is represented on vertical-axis. Color-scale characterizes wavelet coefficients' magnitude from blue to red (i.e. blue the coarser coefficients and red the detailed coefficients). Brighter regions in periodogram specify presence of significant signal-components at detailed times and scales. Curved thick black line is known as Cone of Influence (COI), a bit shaded area shows 5% confidence level and edge-effects. Thick black arrows capture contrasting co-variance of air-passengers carried by the carrier of one country with that of the other and the phase information is captured by direction of the arrows i.e. exact-right arrows show that air-passengers carried time-series of country-x and that of country-y are positively correlated, exact-left arrows show that x and y are negatively correlated, up-right arrows show that x and y are positively correlated and x is leading, whereas, y is lagging, down-right arrows show that x and y are positively correlated x is lagging and y is leading, up-left arrows show that x and y are negatively correlated x is lagging, and down-left arrows show that x and y are negatively correlated x is leading.

RESULTS

Conceding that number of air-passengers carried by the registered air carriers of the countries as one of important economic variable the study aims to examine times varying spectral coherence of air-passenger carried by Pakistani carriers with other Asian economies. General design of the study being data achievement, review of contemporary literature, and analysis of the times series of the number air-passengers carried by the registered carriers of Indonesia, India, Iran, Islamic, Malaysia, Pakistan, Singapore, Sri Lanka, Turkey, Korea, and Japan from January 1, 1970 to December 31, 2019. Classical descriptive statistics and wavelet analysis is used as method of analysis. The literature review is used to set the very outset of the study only. Descriptive statistics provide an overview of the data analyzed that are self-explanatory that the readers and observe there selves given in very easy form of eye-span. On observation of the plots of air-passengers carried by the carriers of every country, it can be

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found that there was steady increase in number of air-passengers in every country clearly lead by Japan Figure-1(j) seconded by Pakistan Figure-1(e) till 2009/2010 but after that there was abrupt increase in the number air-passengers carried till 2019. The wavelet coefficient image as got thru wavelet analysis, where, horizontal axis represents time distance, vertical axis represents spatial frequency inversely related to wavelet scale, whereas, the coefficient-magnitude on color scale, indicates how strongly data are correlated with mother wavelet at assumed frequency & distance. The results of individual wavelet power spectra Figure 2(a) to (j) show that at frequency band 4-128 there is weak correlation between wavelets and mother wavelet, whereas, that there is moderate high correlation between mother and daughter wavelets at 128-1024 frequency bands all over the period under study. There is observed high correlation between mother and daughter wavelets at 1024-4096 frequency bands over the period. In the power spectrum 2(c) of Iran, contour enveloped in black thick line appearing against late 2000 to 2006 (approximately) at frequency bands 512-1024 depicts that there is very strong correlation between mother and daughter wavelets. The effects of changes from 2009/2010 to 2019 where there are steep rapid increase observed on plots lead by Japan is also captured on wavelets but the coefficients are not claimed to be accurate with 95% confidence because of edge effects. The results of the cross wavelet spectra Figure 3(a) to 3(i) show that air-passengers carried by the carriers of selected countries in contrast to that of Pakistan, at frequency band at 4-128 frequency bands all over the period under study there are weak-signs of co-movement of the time series. At frequency band at 128-1024 frequency bands all over the period under study there are moderate strong signs of co-movement of the time series. At 1024-4096 frequency bands over the period is high co-movement of the time series throughout the selected period. The effects of changes from 2009/2010 to 2019 where there are steep rapid increase observed on plots lead by Japan is also captured on cross wavelet transform but the coefficients are not claimed to be accurate at 95% confidence interval because of edge effects. The results of the wavelet coherence spectra Figure 4(a) to 4(i) of time series of air-passengers carried by the registered carriers of selected countries show that at frequency bands 4-128 there are signs of high coherence and correlation between series, whereas, that are mixed patterns of low/high coherence & correlation at 128-256 thru the selected period. At frequency band 256-2048 weak correlation 1980 to 2019 but there are edge effects 2010 to 2019 at frequency bands 1024-4096. There are similar results of almost all the spectra except in some time/frequency bands where there are can be observed patterns of high coherence & correlation (e.g. in 4(c) there is black lined contour pattern as against frequency band 512-1024 localized at approximately 1998 to 2008 where in the correlation is weak between the series). There are also mixed result of lead-lag of the time series. Results also affirm that the series are in phase at most of frequency-time resolutions. It is also valuable to discuss results of the study, implications, contributions, limitations and future recommendations qua actuality keeping in mind the objectives of the study.

DISCUSSION

This section provides a comprehensive discussion on the practical implications of the study for economists, governments, the research community, and industry stakeholders, as well as the theoretical contributions to the understanding of air-transportation dynamics. It also critically addresses the limitations inherent in the study's methodology and data, followed by targeted recommendations for future research aimed at overcoming these constraints and advancing the field.

i) *Discussion on results of the study:* The review of literature reveals that the phenomenon under study is sparingly researched within the context of environmental economics and sustainable management. The authors found a limited number of studies that investigate the environmental impacts of air-passenger transport linkages in Asian emerging economies. However, few existing studies address these issues in a comprehensive and rigorous manner. In fact, hardly any study has explored the dynamic interrelations of air-passenger movements in both time and frequency domains simultaneously, particularly with an eye on their environmental and economic implications. This study extends the frontiers of current literature by integrating air-passenger transport dynamics with an environmental management perspective, focusing on carriers in different Asian countries. It provides a novel framework to quantify the frequency components of the dynamic movement of air-passenger time series without losing time-specific information, crucial for understanding temporal patterns in emissions and resource use. The findings disclose spatial regions indicating the degree and direction (in-phase or out-of-phase) of co-movement among different countries, highlighting potential synergies or conflicts in regional environmental policies. Furthermore, the study illustrates how these interrelationships between air-passenger flows evolve over time and across different frequencies, offering insights into the temporal shifts in environmental pressures linked to aviation. The primary drivers behind the noted increase in air-passengers in

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Asia during 2010 to 2019—economic growth, increased per capita income, expansion of airline networks, and rise of low-cost carriers—exert important implications for environmental management and sustainable economic development. Additional factors such as tourism expansion, airline deregulation, and government liberalization of airport operations further emphasize the complex interplay between economic policy and environmental impact in this region (Hakim, & Merkert, 2019).

ii) *Discussion on implications of the study:*

a) The practical implications of this study are extensive and multifaceted across various stakeholder groups with regard to environmental economics and sustainable management. For economists, the study provides a nuanced understanding of how air-passenger flows among Asian emerging economies dynamically correlate with economic and environmental variables over time and frequency domains. These insights enhance macroeconomic and environmental modeling of regional integration and transport-driven sustainable growth, enabling economists to better forecast and analyze economic interdependencies influenced by air connectivity alongside associated environmental impacts. For governments, the findings offer evidence-based guidance on policy design by revealing periods and frequencies when air-transport linkages strengthen or weaken, which is crucial for infrastructure planning, environmental regulation, and resilience-building in response to shocks such as pandemics or economic fluctuations. This can support more targeted and flexible interventions aimed at optimizing connectivity while minimizing ecological footprints and promoting sustainable travel. Concerning the research community, the study advances theoretical and methodological frontiers by applying wavelet coherence to air-passenger data, addressing gaps in temporal and spectral analyses within transport economics and environmental management. It exemplifies the utility of time-frequency approaches in capturing dynamic relationships otherwise neglected in traditional time-series methods, encouraging further research on multiscale transport interdependencies and their environmental consequences. For industry and companies, including airlines, airport operators, and logistics firms, the dynamic insights into passenger flow correlations inform strategic planning and network optimization with an added lens on environmental sustainability and risk management. Anticipating periods of co-movement or divergence in demand across markets aids in resource allocation, investment decisions, and developing adaptive strategies to enhance operational efficiency while reducing carbon emissions and ecological impacts.

b) Theoretically, the study contributes to the literature by integrating spectral coherence and wavelet analysis with environmental economics and air-transport research, enriching the understanding of how air-passenger transport volumes and their environmental impacts co-evolve across heterogeneous emerging economies. It elucidates the importance of capturing both temporal evolution and frequency-specific interactions, revealing dynamic cause-effect relationships that vary over time and scale with implications for environmental pressures associated with air-transport. This approach deepens the conceptual framework linking transport connectivity to sustainable economic growth, environmental policy effects, and external shocks, fostering a more holistic and dynamic perspective in environmental and transport economics research. Moreover, it reinforces the relevance of non-stationary, multiscale methodologies in empirical investigations, which may inspire new theoretical models incorporating environmental complexities for enhanced explanatory and predictive power in studies of air-transportation and its ecological consequences.

iii) *Discussion on limitations of the study:* There are certain limitations of the study as well; therefore, the findings must be interpreted with caution, considering the following constraints. Firstly, wavelet analysis inherently involves a trade-off between time and frequency resolution; achieving perfect resolution in both domains simultaneously is impossible, which may limit the precision in capturing localized environmental and air-passenger events. Secondly, the quality and granularity of air-passenger data pose challenges, as sample sizes (such as daily or monthly aggregated passenger counts) may be relatively small compared to other transport or environmental data, increasing susceptibility to noise and short-term fluctuations that can obscure underlying trends relevant to environmental impact assessments. Thirdly, while wavelet coherence reveals correlations and co-movements at different frequencies and times between countries, it does not establish causality or fully capture the complex, potentially nonlinear interdependencies influencing air-passenger volumes and their environmental consequences across economies. Fourthly, external shocks or events such as pandemics, policy changes, or economic crises may induce structural breaks or non-stationarities in the data, complicating wavelet interpretation and possibly requiring supplementary approaches to address abrupt regime changes not easily reflected in spectral coherence alone, especially regarding sudden shifts in environmental pressures. Fifthly,

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the methodology primarily focuses on registered air carriers and passenger volumes, potentially overlooking informal or unregistered transport modes as well as qualitative factors like passenger satisfaction or infrastructure quality, thereby limiting the comprehensiveness of insights into broader air-transport dynamics and their ecological and sustainability implications.

iv) *Discussion on recommendations for future research to overcome limitations of current study:* Future research should explore the integration of wavelet analysis with complementary methods such as machine learning or econometric causality tests to better address the causality and nonlinear interdependencies that wavelet coherence alone cannot establish. This combined approach can deliver deeper insights into the driving environmental and economic factors influencing air-passenger volume dynamics and their sustainability implications. To mitigate the trade-off between time and frequency resolution inherent in wavelet methods, studies could experiment with advanced multi-resolution techniques or adaptive wavelets tailored to the specific characteristics of air-transport and environmental data, improving the detection of localized, transient events in passenger flows and associated ecological impacts. Enhancing data quality and granularity should be a priority, such as incorporating higher-frequency data (daily or hourly if available), and expanding datasets to include qualitative factors like passenger satisfaction, service quality, infrastructure condition, and environmental performance metrics, which would enrich interpretation beyond mere passenger counts. Future work should explicitly incorporate modeling or adjustment for external shocks, structural breaks, and regime changes (e.g., pandemics, policy shifts) by combining wavelet analysis with change point detection algorithms or regime-switching models, thus better capturing abrupt shifts in both air-transport dynamics and related environmental pressures. Expanding the scope beyond registered carriers and conventional passenger metrics to include informal transport modes, multimodal integration, and detailed environmental impact assessments would provide a more holistic view of air-transport systems and their sustainability challenges in emerging economies. These recommendations collectively emphasize methodological innovation, richer and higher-resolution data, and a broader analytical scope to overcome the inherent constraints of wavelet analysis in capturing the complex environmental and economic dimensions of air-passenger transport systems.

CONTRIBUTION OF THE STUDY

The study reveals the cause–effect relationship over time and simultaneously in the time-frequency space, offering a detailed and dynamic perspective of air-passenger transport connectivity and its environmental implications among Asian emerging economies. It extends the scarce literature on time-varying spectral coherence analysis within the domain of air-transportation and environmental economics, especially focusing on the variable 'air-transport, passengers carried' as defined by the World Development Indicators. The study provides better insights for policymakers, investors, and environmental risk managers by detecting transient correlations and shifts in co-movement periods, thereby enabling more informed decisions to balance growth and sustainability in a volatile and rapidly evolving sector. Moreover, it highlights the utility of the wavelet methodology for rigorously illustrating how interrelationships between air-transport passenger flows—and their associated environmental pressures—evolve through time and across different frequency components without losing time-specific information, thus enhancing the research coverage on dynamic air-transport networks and their sustainability challenges in emerging Asian markets.

CONCLUSION

The investigation presented in this study addresses a vital aspect of modern air-transportation by exploring the time-varying spectral coherence of passenger air-transport across ten strategically important Asian emerging economies, with a focus on environmental sustainability and economic implications. Air-transport plays a pivotal role in fostering regional connectivity, economic growth, and integration, serving as a conduit for trade, tourism, and investment flows within this diverse set of countries, while simultaneously posing challenges related to environmental management and sustainable development. The problem at the core of this research lies in the insufficient understanding of the dynamic and multi-scale interdependencies shaping the evolution of air-passenger volumes amid varying economic conditions, policy environments, and external shocks such as pandemics—factors that also bear significant environmental consequences. While prior studies have addressed air-transport trends individually or bilaterally, few have captured the complex, evolving spectral relationships among a broad regional cohort, highlighting a crucial gap this research aims to fill within an environmental economics framework. Through systematic assembly of sixty-year, country-level panel data from the World Development Indicators database, this study applies wavelet-based methods to dissect the intricate co-movements

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in passenger carriage among Indonesia, India, Iran, Malaysia, Pakistan, Singapore, Sri Lanka, Turkey, Korea, and Japan, with a particular focus on their relationships with Pakistan, thereby providing insights relevant to sustainable transport policy. Methodologically, the study deploys a rigorous framework starting with descriptive statistical analyses and time-series plotting to visually and quantitatively describe longitudinal passenger trends within each country. It then progresses to wavelet individual power spectra analysis to pinpoint dominant oscillation frequencies and temporal localization of passenger transport dynamics along with their implicit environmental pressures. Next, cross-wavelet transform techniques are applied to bivariate country pairs contrasting Pakistan with others to detect joint power and co-movement patterns over time and frequency bands that may influence regional environmental outcomes. The core analytic tool, wavelet coherence, quantifies the strength and phase of localized co-movements between Pakistan and its peer countries, thereby elucidating periods of synchronization, leading and lagging relationships, and potential causality proxies at multiple scales relevant for environmental and economic sustainability. These techniques are selected for their robustness in handling non-stationary, heterogeneous, and multi-frequency economic time series, enabling the capture of transient relationships missed by classical models that inadequately reflect complexity in environmental impacts. The study's literature review and preliminary graphical and spectral analyses establish a rich backdrop of wavelet applications in air-transport and environmental research. Plots of air-passengers carried show steady increase in number of air-passengers in every country clearly lead by Japan seconded by Pakistan 2009/2010 but there after abrupt increase till 2019. Results of individual wavelet power spectra show weak correlation between mother and daughter wavelets at low frequencies, whereas, moderate high correlation at middle level frequency bands over time, and high correlation high frequency bands. Cross wavelet spectra show weak-signs of co-movement of the time series at low frequency bands. There are moderate strong signs of co-movement of the time series at middle level frequency bands, and high co-movement throughout the selected period at high frequency bands. Wavelet coherence spectra show that at low frequency bands there are signs of high coherence, and correlation, mixed patterns of low/high middle level frequency band thru period, and weak correlation high frequency bands. There are edge effects 2010 to 2019 at frequency bands 1024-4096. The results over the time for all times series seems similar except some time/frequency bands where there are patterns of high coherence & correlation. Results also affirm that the series are in phase at most of frequency-time resolutions. Time-series and wavelet power spectra visually highlight important periodicities and fluctuations unique to each country, reflecting economic phases, policy impacts, and their environmental repercussions. Cross-wavelet transforms reveal dynamic synchronicities and divergences that evolve over short, medium, and long-term horizons, while coherence analysis confirms the existence of complex, frequency-dependent connectivity patterns among the selected Asian economies, with Pakistan serving as a critical nodal reference point for coordinated environmental-economic strategies. In conclusion, this research provides a novel, multi-dimensional perspective on how air-passenger transport sectors of Asian emerging economies dynamically interrelate over time and frequency domains, highlighting their environmental management implications. The findings underscore the importance of adopting wavelet-based spectral analysis for capturing the temporal and frequency heterogeneity in regional air-transportation networks and their ecological footprints. Key lessons learned include the recognition that air-transport linkages are neither static nor uniform; instead, they exhibit scale- and time-dependent co-movement patterns influenced by economic cycles, policy shifts, and external shocks, all of which bear consequences for environmental sustainability. This nuanced understanding equips policymakers and industry stakeholders with the capability to design more responsive infrastructure investments, coordinated regional policies, and resilient operational strategies that effectively balance growth with environmental management. Overall, the study advances both theoretical knowledge and practical insights on the spectral coherence characteristics of air-transportation, marking a significant step toward integrating sophisticated time-frequency analytical approaches in environmental economics, transport sustainability, and regional integration studies.

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