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Comparative Analysis of Flight Volume Effects on COVID-19 and Influenza Transmission Across Variable Control Intensities, 2019–2024

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Background. Air travel has played a critical role in the global spread of infectious diseases, facilitating rapid movement of pathogens across continents. This study quantifies the effects of intercontinental flight volumes on both influenza and COVID-19 transmission patterns across countries with varying intensities of public health interventions.

Methods. We analyzed monthly global passenger numbers from January 2019 to July 2024, coupled with comprehensive surveillance data on both pathogens. Using a hierarchical Bayesian linear mixture modeling framework, we examined the relationship between flight volumes and disease activity while accounting for heterogeneity in public health and social measures.

Results. Our analysis reveals that increased flight volumes were significantly associated with both influenza activity and COVID-19 case and mortality rates, with Asian flight spreading rate demonstrating the strongest association with influenza transmission and COVID-19 case rates. These effects were consistently stronger for COVID-19 than influenza and more pronounced in countries with less stringent control measures.

Conclusions. The comparative approach provides unique insights into how different respiratory pathogens respond to aviation-mediated exposures, demonstrating that targeted travel restrictions can effectively impede disease transmission when implemented alongside appropriate public health interventions. These findings have important implications for the development of pathogen-specific strategies for mitigating the international spread of emerging respiratory threats.

Keywords. air travel; COVID-19; influenza; disease transmission; public health measures.

Air travel plays a crucial role in infectious disease spread, creating unprecedented pathways for pathogens to cross global boundaries within hours. The confined environment of aircraft cabins creates ideal conditions for respiratory disease transmission [1]. Influenza spread is directly linked to air travel through both imported cases and in-flight transmission [2]. Findlater et al [3]. showed air travel accelerates influenza transmission, while network analyses demonstrate airline connectivity patterns effectively predict epidemic risk [4]. Multiple studies have documented SARS-CoV-2 transmission linked directly to air travel, with contact tracing studies identifying secondary cases from flight-associated exposures [5–7]. Similar evidence exists for influenza, where phylogenetic analyses have tracked the global spread of viral variants along major air travel corridors [2, 8, 9].

COVID–19 prompted unprecedented aviation disruptions, as countries imposed varying travel restrictions, creating a natural experiment to assess how flight volume changes influence disease transmission [10]. To curb importation risk, many governments implemented targeted aviation measures, such as China's circuit breaker policy, temporary suspension of specific flights when imported cases exceed set limits, and enhanced testing requirements [1]. Notably, COVID-19 prevention measures simultaneously affected transmission patterns of other respiratory pathogens, particularly influenza [11].

Although growing evidence links air travel to the spread of infectious diseases, quantitative analyses of travel–volume impacts remain limited and fragmented. Most studies examine COVID–19 or influenza separately, with few comparing flight–volume effects under varying control intensities. Here, we examined the relationship between intercontinental flight volumes and transmission of both COVID-19 and influenza across countries with varying public health control intensities.

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METHODS

Data Source and Processing

This study combines multiple sources of data, including epidemiological data streams for influenza and COVID-19, and travel volume data.

Country–level influenza data were obtained from WHO FluNet (https://www.who.int/tools/flunet), a global web–based virological surveillance platform launched in 1997. Influenza activity, unlike COVID–19 metrics, was measured as the percentage of laboratory–tested samples yielding positive results (positivity rate), enabling cross–country comparisons despite varying testing capacities. The analysis covered January 2019 to July 2024 to establish a pre–pandemic seasonal baseline. To ensure data quality and sufficient sample sizes for robust statistical analysis, we retained only country–year observations with ≥20 reporting weeks and ≥100 processed specimens [12]. After excluding countries with substantial missing data, the final dataset comprised 78 countries with complete information across all three sources.

The COVID-19 data were sourced from the WHO COVID-19 Dashboard, which provided official daily counts of COVID-19 cases and reported deaths from countries, territories, and regions. For our analysis, we utilized both the daily new confirmed cases and cumulative death counts, which were aggregated to monthly totals and converted to population-adjusted rates (per 100 000 population) using World Bank population estimates. Our study period for COVID-19 data spans from January 2020 to July 2024.

To complement our global analysis and investigate whether similar patterns are observable at a subnational level, we collected state-level data from the United States. US state-level COVID-19 and influenza surveillance data were obtained from the Centers for Disease Control and Prevention (CDC) for a shorter study period (January 2019 to October 2023 for influenza; January 2020 to May 2023 for COVID-19).

We collected the country-level flight data and domestic flight volume data between US states from the OAG analyzer (https://analytics.oag.com/analyser-client/home). Monthly travel data were derived using origin-specific bookings.

We define the intensity of public health and social measures (PHSMs) by the Oxford COVID-19 Government Response Tracker (OxCGRT) [13]. The OxCGRT collected comprehensive information on pandemic response measures enacted by governments worldwide, and also US state level, and when these measures were implemented. For our analytical framework, we constructed separate regression models for each of three key metrics as adjustment variables in our regression analyses: stringency index (SI), containment health index (CHI), and government response index (GRI), allowing us to account for variation in policy responses when examining the relationship between air travel and disease transmission.

Statistical Methods

We developed Bayesian generalized linear multivariate models to examine the relationship between flight volume and disease incidences across countries with varying levels of COVID-19 control measures.

Outcome Measures

Based on country-level data, we constructed monthly time series for three primary outcome measures: (1) influenza activity rates, (2) COVID-19 case rates (per 100 000 population), and (3) COVID-19 death rates (per 100 000 population). COVID-19 death rates are included to complement case data, as they may be less affected by variations in testing capacity and reporting standards across countries [14]. Influenza activity was defined as the percentage of laboratory samples that tested positive for influenza virus. For both influenza and COVID-19 metrics, we addressed missing values and zeros in the time series by imputing them with half of the minimum nonzero observed value for the respective country, to prevent issues with logarithm transformations while maintaining the relative scale of the data.

We defined "flight spreading rate" of a pathogen as the product of monthly inbound passenger volume from a given origin country to the study destination and the corresponding origin–country pathogen incidence rate, assuming that the number of infected travelers is proportional to local incidence of that pathogen.

Analytical Approaches

We used Bayesian linear mixture modeling to examine the relationship between flight volumes and disease transmission rates. After summing the country-level flight spreading rate by continents, continent-level flight spreading rate from six continents (Africa, Asia, Europe, North America, Oceania, and South America) were treated as continuous predictors in our regression models. To account for the substantial differences in passenger numbers across continents, we standardized the flight volume data using min–max scaling, transforming values to a 0–1 range. Disease metrics were log-transformed. The resulting incidence rate ratios (IRRs) represent the multiplicative effect on disease metrics when flight volume from a specific continent increases from its minimum to maximum value.

We also tested considering the flight spreading rate as categorical variables that may capture the nonlinearity. To account for the substantial variability in flight spreading rate, we categorized the continent-level flight spreading rates into five ordinal levels (0–4), with level 0 representing the lowest flight spreading rate. Level 4 (the highest flight spreading rate) is the reference group. As another sensitivity analysis, we directly use flight volume, without assumptions on pathogen prevalence.

Model Specification

Our analysis consisted of three separate Bayesian linear mixture models, each estimating the association between flight spreading rates (as fixed effects) and one of our three outcome variables: (1) monthly influenza activity rates, (2) monthly COVID-19 case rates, and (3) monthly COVID-19 death rates. All models were adjusted for the intensity of PHSMs, proxied by GRI, and included country-specific random intercepts to account for unmeasured heterogeneity between countries, such as differences in surveillance systems, healthcare infrastructure, and population demographics.

To mitigate false positives (Type I errors), we adopted a conservative approach by using informative priors with a restrictive normal distribution, N (0, 0.25), where a mean of zero denotes no effect of flight volumes on disease transmission rates [15]. Additional sensitivity analyses employed SI or CHI instead of GRI, and assessed interactions between flight spreading rates and PHSM intensity. We also conducted further temporal sensitivity analysis by restricting the analyses to specific periods to ensure robustness (Supplementary Appendix section 2). Details of implementation and converge checking was in Supplementary Appendix Section 2–3.

US State-Level Analysis

We aggregated the 50 US states into five geographical regions: Northeast, Southeast, Midwest, West, and Southwest, based on standard US Census Bureau regional classifications [16]. We applied the same analytic approach using Bayesian linear mixture modeling framework to the US data as was used in our global analysis, with state-specific random intercepts to account for unmeasured heterogeneity between states and adjusting intensity of PHSMs.

RESULTS

Changes in Flight Volumes, Influenza Activity and COVID-19 Activity From 2019 to 2024

Supplementary Figures 1 and 2 demonstrate the profound impact of the COVID-19 pandemic on global aviation from 2019 to 2024. In Supplementary Figure 1, the geospatial visualizations display consistent flight routes across 6 years, whereas the time series in Supplementary Figure 2 depicts pronounced fluctuations in route volumes. Global flight passenger numbers plummeted in early 2020, bottoming out mid–year, before gradually recovering from 2021 onward. The pandemic's impact varied significantly by region; Asian connectivity suffered the most severe reductions, with a prolonged depression in travel volume between 2020 and 2022, particularly for routes connecting with Europe, North America, and Oceania. By contrast, European volumes began rebounding in mid–2021, nearing pre–pandemic levels by 2023, reflecting regional differences in pandemic response stringency.

US domestic flight patterns (Supplementary Figure 2, panels C and D) show more uniform regional impacts and faster recovery, returning to prepandemic levels by early 2022, though still exhibiting seasonal fluctuations.

Figure 1, Supplementary Figures 4 to 9 display the temporal dynamics of influenza and COVID-19 from 2019 to 2024 across global regions and US state levels. Global influenza activity showed marked seasonality before the pandemic, with peak positivity exceeding 30% in multiple regions during 2019–early 2020. Activity was sharply suppressed in 2020–2021 alongside COVID–19 containment measures, and then resurged unevenly from late 2021, with Europe recording notable increases by 2024. COVID–19 case rates displayed distinct waves, peaking in Oceania (>7%) in early 2022 and in Europe (>6%) thereafter. While early COVID-19 waves (2020–2021) showed substantial regional variation, by 2022–2023 the patterns became more synchronized globally before declining toward endemic levels by 2024. COVID-19 mortality exhibited different patterns than case rates, with South America recording the highest death rates in mid-2021 (>3.5 per 10 000), despite higher case rates elsewhere. US data exhibited more uniform regional patterns and a pronounced influenza resurgence in 2022–2023.

Relationship Between Influenza Activity and Flight Volumes

The flight volume from Asia demonstrated a positive association with influenza transmission (IRR: 1.21, 95% CI: 1.19–1.23). This association remained significant across all sensitivity analyses, indicating a robust relationship between Asian flight volumes and influenza spread. European flight volume (IRR: 1.05, 95% CI: 1.03–1.08) and North America flight volume (IRR: 1.12, 95% CI: 1.09–1.15) also showed consistent significance across all time periods analyzed. Other continental flight volumes showed variable associations that were not consistently significant across sensitivity analyses. As expected, domestic flight patterns within the United States revealed weaker and inconsistent associations with influenza transmission compared to global patterns, likely reflecting the availability of alternative transportation modes within the country.

The significant positive associations for Asian, European, and North America flight volumes remained consistent when employing alternative modeling strategies, including: (1) incorporating interaction terms between GRI and travel volumes rather than simple adjustment (Supplementary Figure 10); (2) treating flight volumes as categorical rather than continuous variables (Supplementary Figure 11); (3) substituting SI or CHI for GRI as control measures (Supplementary Figures 12 and 13). The significant positive associations for Asian flight volumes remained consistent when using raw travel volume without multiplication by local disease rates (Supplementary Figure 14).

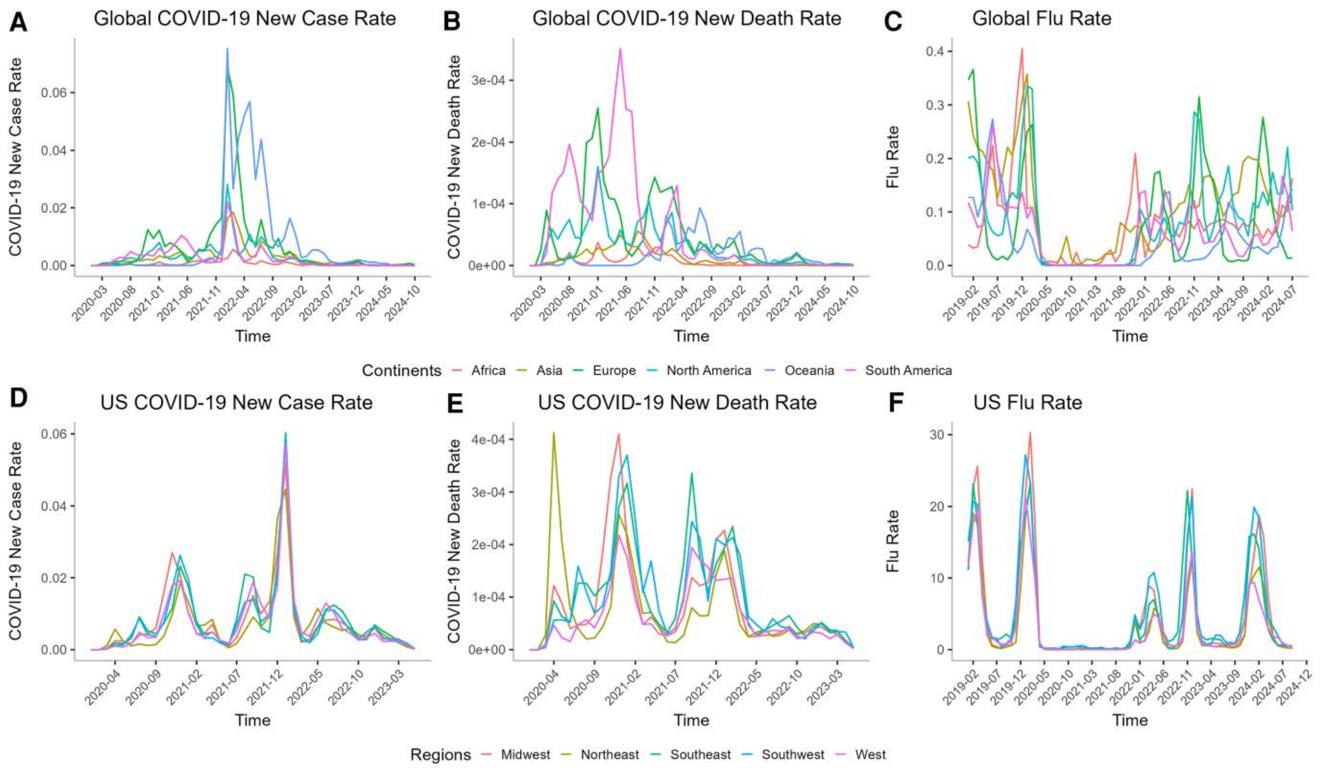

Figure 1. Time series of the Global and US COVID-19 new case rate, COVID-19 new death rate, and Influenza positive rate. *A*, The time series of the Global COVID-19 new case rate. *B*, Time series of the Global COVID-19 new death rate. *C*, The time series of the Global influenza positive rate. *D*, The time series of the US COVID-19 new case rate. *E*, The time series of the US COVID-19 new death rate. *F*, The time series of the American influenza positive rate.

Relationship Between COVID-19 Transmission and Flight Pathogen Spreading Rate

COVID-19 transmission, measured through both case rates and death rates, showed consistent associations with intercontinental flight volumes. For case rates (Figure 2), higher flight volumes from Asia (IRR: 1.72, 95% CI: 1.47–2.02), Europe (IRR: 1.45, 95% CI: 1.42–1.48), and North America (IRR: 1.21, 95% CI: 1.07–1.35) were all significantly associated with increased COVID-19 case rates. When examining COVID-19 mortality (Figures 3 and 4), which may more reliably reflect disease burden due to less variation in reporting standards across countries, Asian flight spreading rate maintained a significant positive association, consistent with case findings. North American flight spreading rate also showed a strong positive association with mortality, though the magnitude of this association was notably higher than observed for case rates.

The significant positive associations for Asian, European and North America flight volumes remained consistent when employing alternative modeling strategies, including: (1) incorporating interaction terms between GRI and travel volumes rather than simple adjustment (Supplementary Figure 10); (2) treating flight volumes as categorical rather than continuous variables (Supplementary Figure 11); (3) substituting SI or CHI for GRI as control measures (Supplementary Figures 12 and 13). When using raw travel volume without multiplication by local disease rates, these significant positive associations remained consistent, but only Asian flight volume remains significant for 2023–2024 (Supplementary Figure 15).

Unlike the consistent patterns observed for international flight volumes, the relationship between US domestic flight volumes and COVID-19 transmission showed variable patterns across regions. Southwest flight volume exhibited the strongest positive associations with both COVID-19 case rates (IRR: 2.71, 95% CI: 2.23–3.29) and mortality rates (IRR: 6.27, 95% CI: 4.70–8.38), and remained consistent when the data from 2020 were excluded (Figure 5). This remained consistent in the sensitivity analyses mentioned above (Supplementary Figures 10–14). However, when using raw travel volume without multiplication by local disease rates, the Southwest flight volume exhibited the strongest positive associations with mortality rates but not case rates (Supplementary Figure 15).

DISCUSSION

This study employed a Bayesian linear mixture modeling framework to quantify relationships between flight volumes and COVID-19 and influenza transmission across 78 countries and the US states from 2019–2024. Our analysis revealed

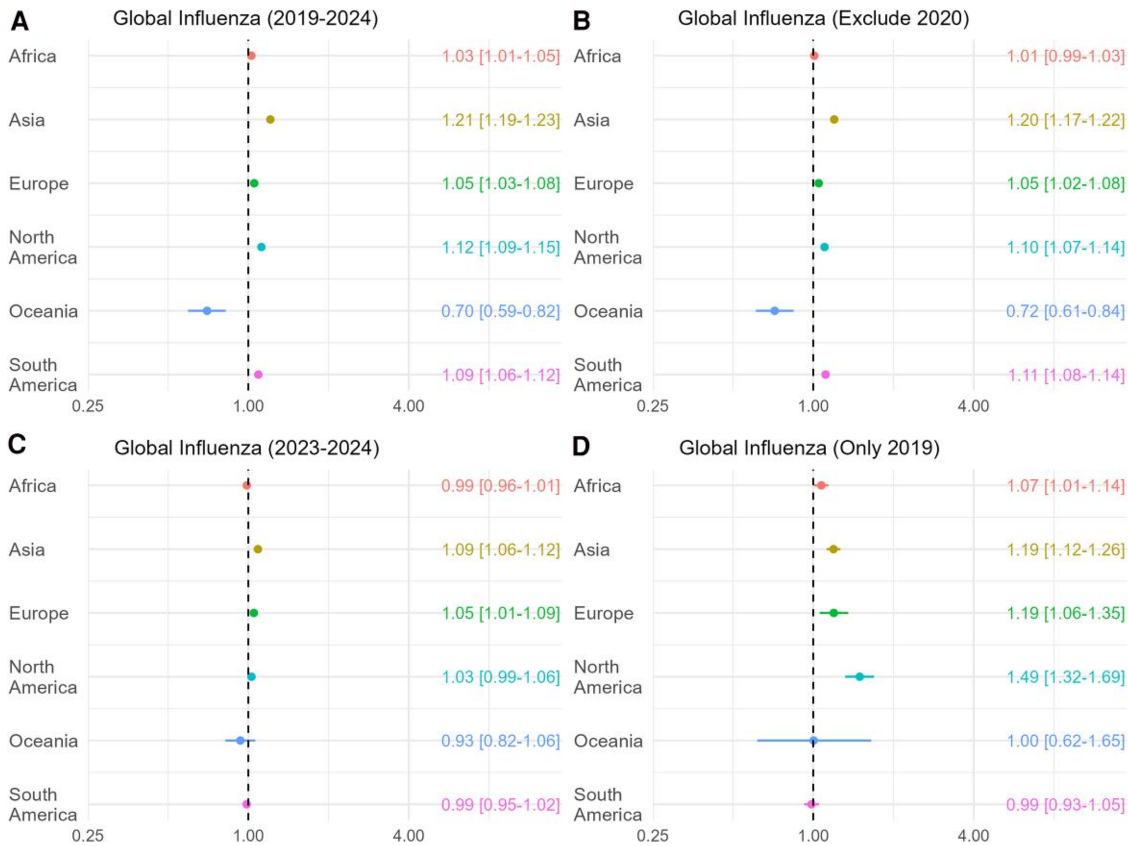

Figure 2. The regression result for the US influenza positive rate, adjusted by GRI. *A*, Regression results for US influenza positive rate from 2019 to 2023. *B*, Regression results for US influenza positive rate based on data excluding 2020 (years 2021–2023). *C*, Regression results for US influenza positive rate from 2023 to 2023. *D*, Regression results for US influenza positive rate only in 2019.

significant associations between intercontinental flight volumes and increased disease activity, with important variations by geographic region and pathogen type. Domestic flight volumes showed weaker associations with transmission compared to international patterns.

We found strong positive associations between flight volumes and both COVID-19 and influenza transmission, with air travel from Asia, Europe, and North America showing particularly consistent relationships. Higher international passenger volumes directly increased infectious disease importation frequency [17], subsequently driving community transmission in destination countries [18]. This relationship persisted when analyzing raw flight volumes without incorporating origin country disease prevalence, confirming passenger volume as a robust predictor of cross-border transmission.

Asymptomatic or presymptomatic travelers may board flights without detection by standard screening protocols. International aviation networks facilitate global variant dissemination [2]; with recent analyses directly linking Omicron's rapid spread to specific flight routes [19]. During intermediate epidemic phase, imported cases via air travel have diminished impact relative to indigenous transmission, though sporadic introductions continue enriching viral diversity and may spark localized microclusters [20]. During endemic circulation, air travel mainly introduces individual cases or new variants, but local transmission and domestic policies predominantly determine disease patterns [21]. The consistency of our findings across multiple sensitivity analyses underscores the robust relationship between international flight volumes and respiratory disease transmission for both pathogens studied.

We estimated a flight-related IRR for Oceania of <1. After applying inclusion criteria, the Oceania dataset comprised only Australian data. Given Australia's strict border management [22], rigorous passenger screening [23], and seasonal misalignment during the study period, this subunitary estimate likely reflects negative bias from reduced source-end risks and policy-responsive flights contractions, rather than an inhibitory effect of flights on transmission. Sensitivity analysis omitting Oceania data showed negligible impact on estimated flight spreading rates for remaining continents, reinforcing our findings' robustness.

Asian flight volumes showed particularly strong associations with both COVID-19 and influenza transmission, supported by several underlying mechanisms. Asia serves as a critical

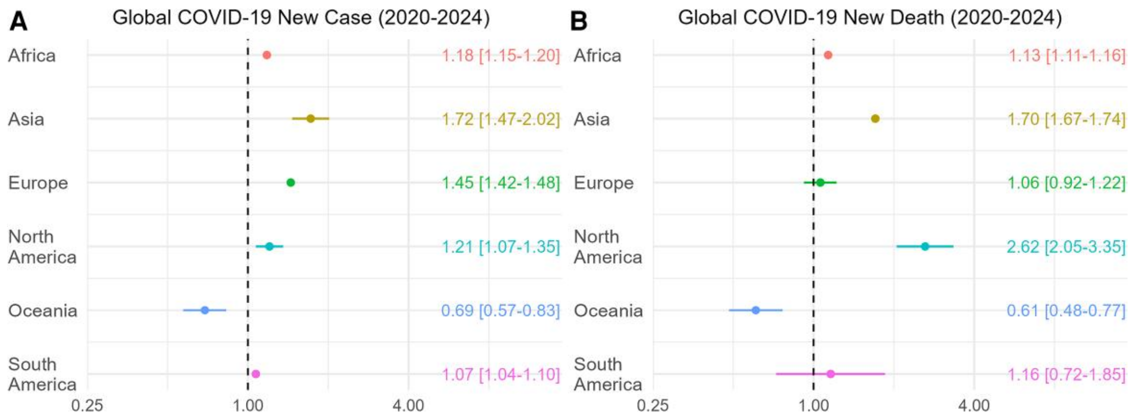

Figure 3. The regression result for the global COVID-19 new case rate and COVID-19 new death rate, adjusted by GRI. *A* and *B*, Regression results for global COVID-19 new case rates and global COVID-19 new death rates from 2019 to 2024.

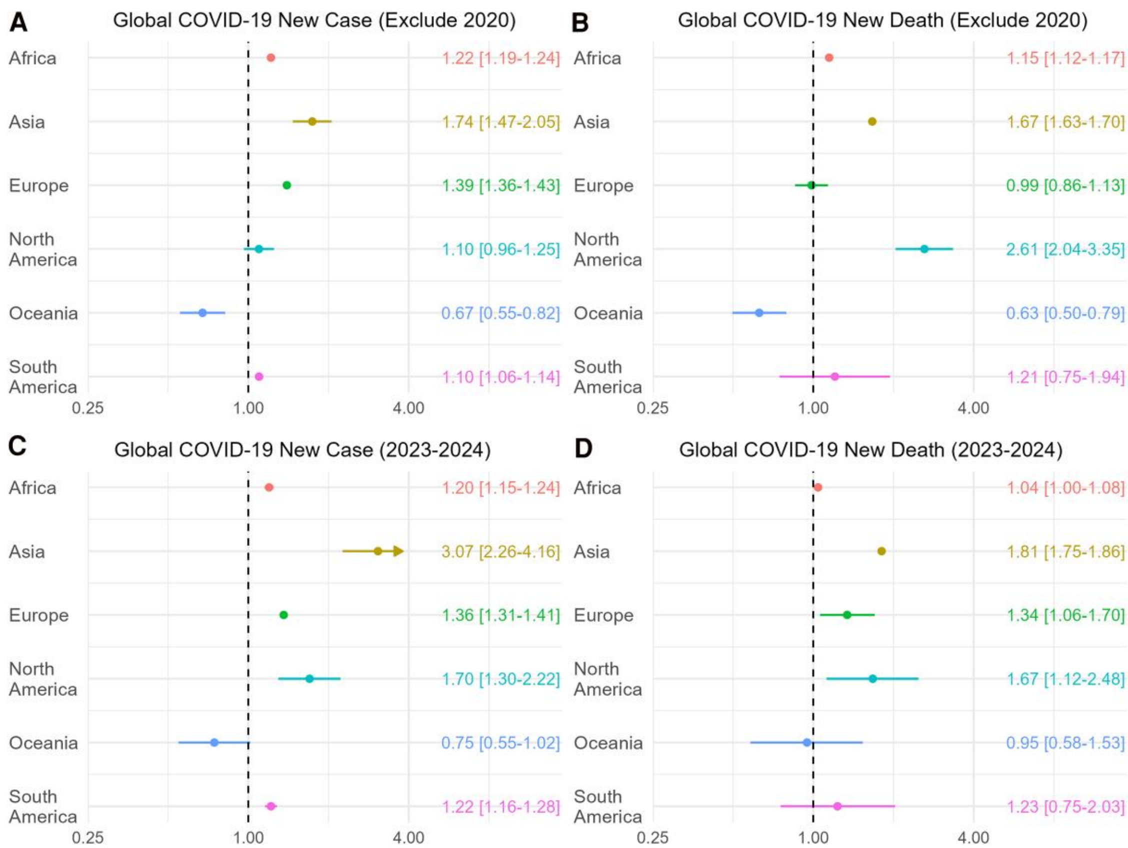

Figure 4. The regression result for the global COVID-19 new case rates and global COVID-19 new death rates, adjusted by GRI. *A* and *B*, Regression results for global COVID-19 new case rates and global COVID-19 new death rates based on data excluding 2020 (years 2021–2024). *C* and *D*, Regression results for global COVID-19 new case rates and global COVID-19 new death rates from 2023 to 2024.

epicenter for respiratory virus emergence and evolution, with East, South, and Southeast Asia functioning as important reservoirs for novel influenza strains and viral diversity. The region's dense population centers, proximity of humans to livestock, and ecological conditions create ideal environments for viral emergence and reassortment [24]. Influenza viruses frequently originate in Asia before spreading globally through well-established air travel corridors to Europe and North America

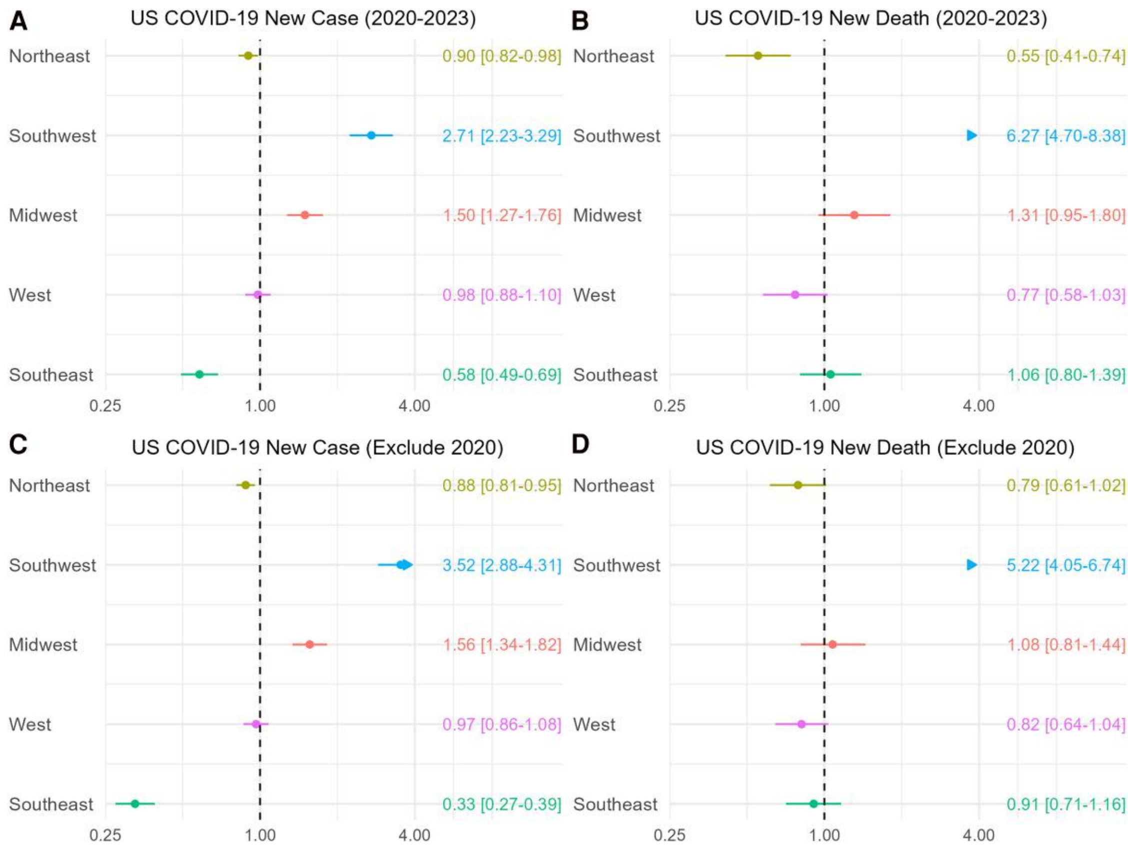

Figure 5. The regression result for the US COVID-19 new case rates and US COVID-19 new death rates, adjusted by GRI. *A* and *B*, Regression results for US COVID-19 new case rates and US COVID-19 new death rates from 2020 to 2023. *C* and *D*, Regression results for US COVID-19 new case rates and US COVID-19 new death rates based on data excluding 2020 (years 2021–2023).

[9, 25]. Previous studies demonstrate that areas with high connectivity to major Asian airports experienced earlier and more intense transmission during the seasonal influenza outbreaks [2, 3, 26]. While some countries in Asia, such as China, restricted international travel, other major Asian countries experienced significant COVID-19 outbreaks while maintaining substantial international flight connectivity, explaining why aggregated Asian flight volumes remained strongly associated with global transmission [27].

Although flight volumes influenced transmission of both COVID-19 and influenza, the association was consistently stronger for COVID-19. COVID-19's longer incubation period (2–14 days vs 1–4 days for influenza) and significant proportion of asymptomatic transmission facilitate undetected spread during air travel [28, 29]. Viral subtype characteristics further differentiate transmission patterns: H3N2 influenza demonstrates stronger dependence on population movements due to its rapid antigenic drift, while influenza B exhibits less sensitivity to air traffic networks [25]. SARS-CoV-2's transmission dynamics parallel influenza A/H1N1pdm09 more closely than SARS-CoV-1, with close-contact accounting for ~70% of H1N1 in-flight transmission cases [30].

Environmental factors and variant emergence further modulate these relationships. Both pathogens show sensitivity to temperature and humidity variations [31], but COVID-19's higher reproduction number and super spreading capacity amplify its association with international travel. The emergence of highly transmissible SARS-CoV-2 variants, particularly Omicron, accelerated cross-border spread via aviation networks [32], with significant implications for future pandemic preparedness strategies.

COVID-19 case rates and mortality rates provided complementary metrics in our analysis. Case data offered greater sensitivity and earlier detection of transmission patterns but was vulnerable to variations in testing capacity and reporting protocols. Mortality data, while more reliable for cross-country comparisons, had inherent time lags and reflected healthcare capacity differences [14, 33]. Examining both metrics and finding consistent associations with flight volumes strengthened our findings' credibility while acknowledging limitations of any single disease metric in a global pandemic with heterogeneous surveillance systems.

To complement our global analysis, we extended our investigation to examine subnational transmission patterns within the United States. US domestic flight volumes showed weaker

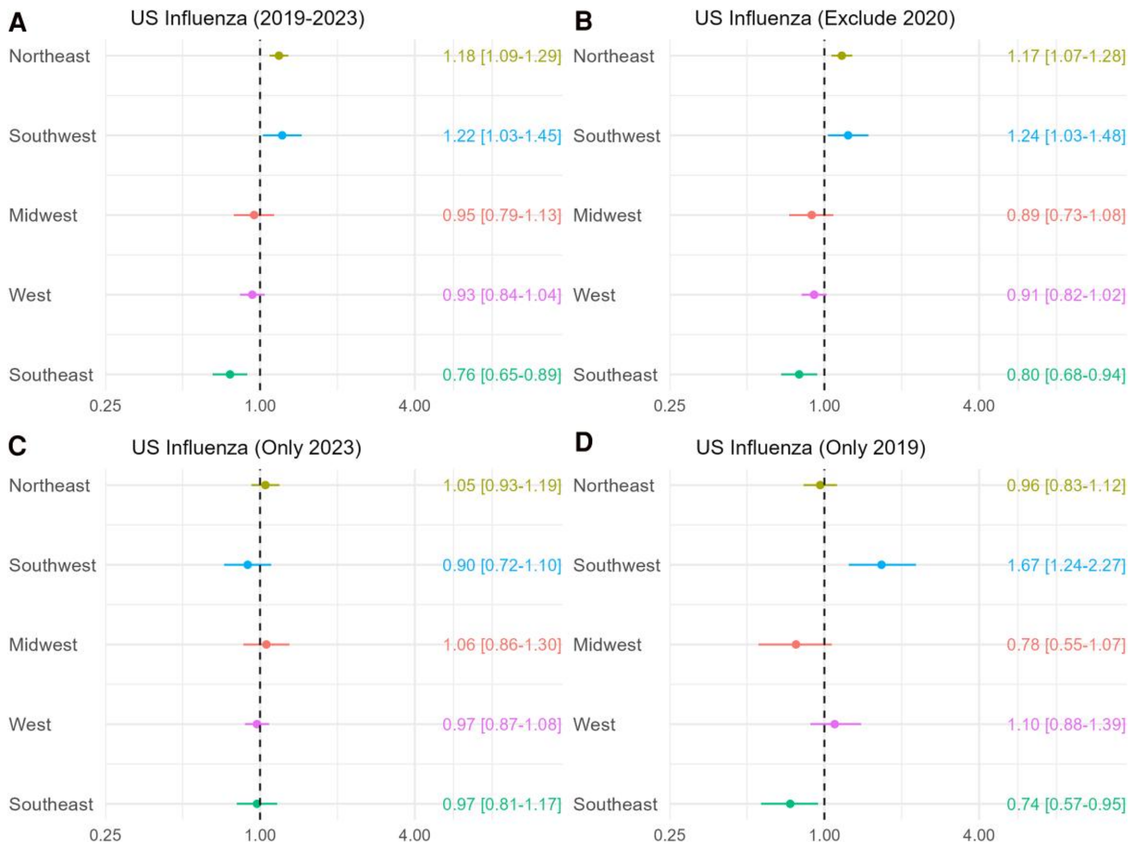

Figure 6. The regression result for the influenza positive rates, adjusted by GRI. *A*, Regression results for influenza positivity rates in the global region from 2019 to 2024. *B*, Regression results for influenza positivity rates in the global region on data excluding 2020 (year 2019, 2021–2024). *C*, Regression results for influenza positivity rates in the global region from 2023 to 2024. *D*, Regression results for influenza positivity rates in the global region in 2019.

and more inconsistent associations with disease transmission compared to international flight patterns. This difference likely reflects the availability of alternative transportation modes within countries, diluting aviation's specific contribution to domestic disease spread, consistent with a previous study reported more modest effects for domestic flights [8].

The COVID-19 pandemic significantly altered global influenza patterns through widespread nonpharmaceutical interventions [34]. Our temporal sensitivity analyses revealed distinct period effects in the relationship between flight volumes and disease transmission. During the prepandemic period (2019), flight volumes demonstrated stronger correlations with influenza activity, suggesting this relationship is modulated by prevailing public health measures and background disease prevalence. The gradual relaxation of COVID-19 restrictions in late 2022 coincided with influenza resurgence (Figure 1), likely intensified by diminished population immunity resulting from reduced exposure during the pandemic [35].

Time-varying confounding represents an important limitation in our analysis. Flight volume recovery coincided with the emergence of highly transmissible variants (Delta/Omicron), while seasonal travel patterns may align with influenza seasonality independent of causal relationships. Our temporal sensitivity analyses (Figures 3, 4 and 6) revealed that associations varied across different time periods, though these changes could reflect reduced sample sizes in temporal subsets rather than spurious correlations. While 2019-only analyses suggest that flight-influenza associations existed before COVID-related disruptions, seasonal confounding potential remains. The monthly resolution limits our ability to distinguish genuine transmission effects from coincidental temporal patterns. Future research should incorporate higher-frequency data, seasonal indicators, and explicit de-seasonalization techniques to better disentangle mobility-driven transmission from concurrent epidemiological cycles.

Our findings suggest that international flight restrictions can impede respiratory pathogen spread, particularly in countries with less stringent domestic controls. From a policy perspective, targeted, time-limited international travel measures may be effective as part of integrated outbreak response, particularly in early pandemic stages. However, for endemic or seasonal infections, political and economic costs make such measures impractical, underscoring the need for robust surveillance and rapid domestic containment strategies. Effective policy requires integrated strategies beyond travel restrictions alone. Without early detection and prompt action, travel restrictions offer limited effectiveness [36], while imposing significant economic costs on international trade and tourism [37]. Sustainable approaches includes in-flight preventive measures such as enhanced ventilation, routine disinfection, and mandatory mask wearing [38, 39]. Decision-makers should implement comprehensive strategies tailored to specific pathogens and variants [5, 35, 40, 41], balancing public health protection with economic and social considerations based on pathogen characteristics, outbreak phase, and local context [42–45].

This study has some limitations. First, our analysis was restricted to 78 countries with sufficient influenza surveillance data, potentially reducing generalizability to regions with weaker monitoring systems. Second, we did not adjust for potential under-reporting or bias in infectious disease case counts, particularly in low-capacity regions. More fundamentally, systematic differences in surveillance capacity between high-connectivity and low-connectivity countries may partially confound our observed associations, as economically developed countries with extensive air travel networks typically maintain more robust disease detection and reporting systems. Third, the ecological study design constrains causal inference. Countries with high flight connectivity participate in complex aviation networks where they both import and export cases. Although random effects can absorb baseline differences between countries, our design focuses on inbound flight associations with destination country disease patterns. The observed associations reflect the epidemiologically meaningful relationship between international connectivity and disease transmission patterns. Future research could model bidirectional flight networks to provide additional insights into global disease dynamics. Finally, we did not consider potential cross–immunity or coinfection dynamics between COVID–19 and influenza, which may influence transmission during cocirculation periods and merit future study using individual–level travel and infection data.

In conclusion, international flight volumes significantly influenced the global spread of both COVID-19 from 2020 to 2024 and influenza from 2019 to 2024, with stronger associations observed for COVID-19. This difference highlights how emerging pathogens with limited population immunity are particularly vulnerable to aviation-mediated transmission. Our findings advance understanding of how global mobility shapes infectious disease dynamics and underscore the importance of tailored aviation-related interventions in pandemic preparedness. Future response strategies should incorporate these differential impacts when implementing travel-related containment measures, balancing public health protection with socioeconomic considerations.

Supplementary Data

Supplementary materials are available at *The Journal of Infectious Diseases* online (http://jid.oxfordjournals.org/). Supplementary materials consist of data provided by the author that are published to benefit the reader. The posted materials are not copyedited. The contents of all supplementary data are the sole responsibility of the authors. Questions or messages regarding errors should be addressed to the author.

Notes

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Potential conflicts of interest. All authors: No reported conflicts.

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