The burden of El Niño–Southern Oscillation-related dengue attributable to anthropogenic climate change: a multicountry modelling study

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Summary

Background Dengue is known to be associated with El Niño–Southern Oscillation (ENSO) but the size of the effect is unclear, as is the influence of anthropogenic climate change (ACC). We aimed to quantify the associations between ENSO and dengue risk in 21 countries, and to estimate the contribution of ACC to the ENSO-related dengue burden.

Methods We collected monthly dengue cases and observed and simulated climate data from 21 countries including 1237 locations from 2000 to 2019. We characterised Eastern Pacific (EP) and Central Pacific (CP) ENSO exposures for each location based on the E and C indices and their respective teleconnections. Location-specific association between ENSO exposure and dengue cases was estimated using negative binomial generalised linear model combined with best linear unbiased predictions. We also estimated the ENSO-related dengue burden under scenarios with and without ACC.

Findings For each standard deviation increase in EP-El Niño strength and CP-La Niña strength, the overall risk of dengue cases across locations changed by 23·70% (95% CI 21·50 to 25·94) and –9·07% (–9·91 to –8·21), respectively. During 2000 to 2019, 4·45% (95% empirical CI [eCI] 3·75 to 5·32) and –3·34% (–4·01 to –2·64) of dengue cases were attributable to EP-El Niño strength and CP-La Niña strength, respectively. ACC accounted for 48·64% (95% eCI 38·01 to 60·19) of the EP-El Niño-attributable dengue increment and 33·05% (28·66 to 38·25) of the CP-La Niña-attributable reduction. These estimates corresponded to 403 197 (95% eCI 315 109 to 498 940) and –205 641 (–238 030 to –178 329) dengue cases across 1237 locations, respectively. The associations with ENSO varied strongly across the 21 countries.

Interpretation This study presents new model-based evidence of the strong associations between ENSO and dengue risk at a multicountry level, and suggests that the contribution of ACC to the effects of ENSO might differ geographically.

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Introduction

Dengue is a mosquito-borne disease that has established both endemic and epidemic transmission patterns globally in past decades.[1] Currently, nearly half of the world's population is at risk of dengue, with annual infections estimated between 100 million and 400 million cases, imposing severe health-care costs and labour lost.[2] Managing the burden of dengue remains complicated by the lack of specific antiviral treatments, despite the recent approval of certain vaccines.[3] Meteorological factors are being significantly associated with dengue outbreaks, such that rising temperatures and altered rainfall patterns might promote virus external incubation and mosquito survival and breeding.[4] In this context, the impact of El Niño–Southern Oscillation (ENSO), a major trigger of meteorological anomalies globally, on dengue risk has attracted increasing attention.[5]

ENSO arises from coupled ocean–atmosphere interactions in the tropical Pacific, characterised by anomalous warm (El Niño) and cold (La Niña) phases.[6] Spatially, ENSO manifests in two distinct patterns: an Eastern Pacific type (EP-ENSO, quantified by E index), where warm events generally exceed cold events in intensity, and a Central Pacific type (CP-ENSO, quantified by C index), where La Niña phases often dominate in strength.[7,8] ENSO shapes global weather with spatial heterogeneity through long-distance atmospheric teleconnection.[6,9] For example, El Niño phases typically induce dry conditions in south and southeast Asia, southern Africa, and northern Brazil, but trigger heavy rainfalls in central America, northern Peru, Ecuador, and equatorial east Africa.[10] The opposite meteorological events generally occur during La Niña phases.[10] These teleconnected weather events could largely

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Research in context

Evidence before this study

We searched PubMed, Web of Science, and Google Scholar from database inception to Feb 25, 2025, using the terms: ("El Niño" OR "La Niña" OR "ENSO") AND ("dengue" OR "dengue fever") AND ("burden" OR "risk" OR "climate change" OR "anthropogenic"). Previous evidence indicates that El Niño–Southern Oscillation (ENSO) might influence dengue transmission by altering temperature and precipitation patterns. However, most studies were limited in spatial scale (eg, in a specific location), and few attempted to quantify the burden of dengue associated with ENSO across countries. Critically, no studies to date have quantified the extent to which anthropogenic climate change (ACC) has contributed to ENSO-related dengue risk.

Added value of this study

To our knowledge, this is the first multicountry analysis to quantify the burden of dengue associated with ENSO and to disentangle the contribution of ACC. By integrating monthly dengue surveillance data from 1237 locations in 21 countries with observed and counterfactual climate model simulations, we estimated the proportion of El Niño-related and La Niña-related dengue burden attributable to human-induced climate change. We also identified strong geographical heterogeneity in the effect size of ENSO, providing important insights for region-specific public health strategies towards dengue risk.

Implications of all the available evidence

Our findings suggest that nearly half of El Niño-attributable dengue increment and one-third of La Niña-attributable dengue reduction in the past two decades was driven by ACC, underscoring the urgency of incorporating climate adaptation strategies into infectious disease control programmes. The variation in ENSO–dengue relationships across countries highlights the need for localised risk assessments and interventions. This study reinforces the view that climate change is not just a future threat but a present driver of global health burdens.

explain the inconsistent associations between ENSO and risk of dengue across locations.[4] For example, potential El Niño-driven warming and heavy rainfall were associated with a 4–17% increase in dengue outbreak risk in Peru,[11] whereas El Niño-induced drought was linked to a 73–77% reduction of risk in the Solomon Islands (with La Niña having the opposite effect).[12] A multilocation study is warranted for mapping geographical variation in ENSO-related dengue risk.

ENSO is a dominant mode of interannual climate variability. By comparison, climate change reflects a fundamental shift in the Earth's background state, with human activities considered as its predominant cause especially since the mid-20th century.[13] Isolating this anthropogenic signal in ENSO is complex due to uncertain observed dynamic changes.[13] Nevertheless, a growing body of evidence suggests that anthropogenic warming has been altering the background state (eg, warmer mean sea surface temperature and moister atmosphere, and rising sea levels),[13] and has thereby amplified ENSO's climatic impacts.[13,14] Therefore, it is necessary to quantify the role of anthropogenic climate change (ACC) in ENSO-related dengue burden across locations. Lacking such knowledge impedes region-specific optimisation of public health interventions targeting dengue risk in the context of climate change.

In this study, we used data on dengue cases with climate reanalysis and simulation from 1237 locations in 21 countries to quantify the association between ENSO and dengue risk during 2000–19, and the burden explainable by ACC.

Methods

Historical data

Between Jan 1, 2000, and Dec 31, 2019, monthly dengue cases of 1237 locations (eg, microregions, cities, or other subnational levels) across 21 countries were obtained from multiple sources (figure 1A), including the Chinese Center for Disease Control and Prevention, the Brazilian Ministry of Health, and the Open Dengue dataset.[15] Locations were selected based on the availability of monthly data with complete information on onset date and geographical location (appendix p 9).

During the study period, monthly data on mean sea surface temperature (SST) were collected from the Hadley Centre Sea Ice and Sea Surface Temperature dataset. Monthly data on mean near-surface temperature and total precipitation were obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis dataset. Global population data were collected from WorldPop to calculate population-weighted temperature and precipitation (appendix p 3). We also collected gross domestic product (GDP) and Normalized Difference Vegetation Index (NDVI) to account for potential sources of spatial heterogeneity in the ENSO–dengue association (appendix p 3).

Factual and counterfactual climate datasets

Monthly series of simulated climate data, including SST, near-surface temperature, and total precipitation, were obtained from the Detection and Attribution Model Intercomparison Project (DAMIP) database. Based on physically realistic ENSO dynamics ($\alpha \geq -0{\cdot}17$),[8] we selected simulations of seven climate models (ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, FGOALS-g3, MIROC6, MRI-ESM2-0, and NorESM2-LM) in DAMIP (appendix p 5). This study used two scenarios over 2000–19 (appendix pp 5–6): one representing the factual scenario (with ACC) and the other a counterfactual scenario (hypothetical scenario without ACC).[16]

ENSO strength

Following previous studies,[7,8] we applied the E and C indices to quantify the dynamics of EP-ENSO and CP-ENSO modes, respectively; these two orthogonal indicators effectively quantify EP-El Niño and CP-La Niña (appendix p 3). Then, location-specific teleconnection was used to quantify the heterogeneity in responses to ENSO index (appendix pp 4, 10). Finally, the ENSO (EP-El Niño and CP-La Niña) strength at each location was calculated by multiplying the E and C indices with the monthly teleconnection values respectively. This calculation estimates the degree to which each location's climate is influenced by ENSO, considering: (1) the combined teleconnection of both temperature and precipitation, (2) the multiple sustained months of exposure to ENSO, (3) the fine-scale temporal teleconnection estimation, and (4) the continuous definition of remote teleconnections. The ENSO strength for both factual and counterfactual scenarios was calculated and then bias-corrected following established methods,[8,16] with amplitude defined as the standard deviation (SD) of the quadratically detrended series (appendix pp 5–6).

Estimation of the historical ENSO–dengue relationship

We estimated the association between ENSO strength and dengue cases across locations using a two-stage approach.[4,16] Results were described as percentage change in dengue risk with 95% CI for each SD increase in EP-El Niño strength or CP-La Niña strength.

In the first stage, a negative binomial generalised linear model was applied to quantify the ENSO–dengue association for each survey location at a monthly scale. Categorical month and natural cubic splines with one knot for year were used to control for potential confounding effects of seasonal and long-term trends (appendix p 7).

In the second stage, coefficients of ENSO–dengue curves estimated in the first stage were pooled via a multivariate meta-regression, with GDP and NDVI weighted by population included as predictors to explain certain heterogeneity across locations. Then location-specific estimates were derived from the best linear unbiased prediction (BLUP). This approach improves estimation stability in small areas by borrowing information within the entire ensemble of locations.[16]

The robustness of the main results was examined by supplementary analyses, including the use of different ENSO indices, teleconnection coefficients, varying exposure months, and alternative model specifications (appendix pp 7–8).

Projecting ENSO-related dengue burden attributable to ACC

We quantified the contribution of ACC to ENSO-related dengue cases following methods described previously.[16] First, for each location–scenario–model combination, we calculated the ENSO-related dengue cases by using the monthly simulated ENSO strength series, the monthly baseline dengue cases, and the ENSO–dengue association estimated from BLUP. The ENSO-related dengue cases were aggregated to each country, which were then divided by the total cases to calculate the attributable fraction (AF). The contribution of ACC to ENSO-attributable dengue burden was estimated by comparing AF under the counterfactual scenario with AF under the factual scenario.

To quantify uncertainty, we generated 1000 BLUP coefficients through Monte Carlo simulation and calculated 95% empirical CIs (eCIs) based on the distribution of attributable dengue cases across climate models.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

A total of 18 853 343 dengue cases were reported from 1237 locations during 2000–19 (table). The E and C indices successfully captured the strong EP-El Niño event of 2015–16 and the strong CP-La Niña event of 2007–08 (with peak values of 2·33 and –2·64), respectively (figure 1B). The teleconnection of E and C indices exhibited geographical heterogeneity (figure 1C; appendix pp 13–14), with the highest observed in El Salvador, Cambodia, and Saudi Arabia (values >0·9), and the lowest in Ecuador, Indonesia, and mainland China (data were not available for Hong Kong, Macau, and Taiwan). There was a noticeable divergence in the amplitude of ENSO between factual and counterfactual scenarios (figure 2), with 45·09% (95% CI 36·33–54·47) of EP-El Niño strength and 39·35% (32·74–45·49) of CP-La Niña strength explainable by anthropogenic forcing.

For each SD increase in EP-El Niño and CP-La Niña strengths, the overall risk of dengue cases across 1237 locations changed by 23·70% (95% CI 21·50 to 25·94) and –9·07% (–9·91 to –8·21), respectively (figure 3). EP-El Niño effect had notable geographical heterogeneity, with the largest increases observed in Brazil (37·94% [34·10 to 41·90]) and Peru (26·23% [5·60 to 50·88]) in South America, while the Philippines in southeast Asia showed a decreased pattern (figure 3A). For CP-La Niña effect, the strongest reductions in dengue risk were observed in the Dominican Republic in the Caribbean and Venezuela in South America (from –15·34% to –13·89%), whereas Panama (Caribbean) showed a positive association. Additionally, no significant ENSO–dengue association was observed in several countries (eg, Argentina, Indonesia, and Saudi Arabia).

Location-specific analysis provided more details: EP-El Niño-related dengue risk increased in 997 (81%) of 1237 locations, in particular increasing by over 50% in 173 Brazilian microregions (figure 3B). In comparison, 1023 (83%) of 1237 areas showed decreased dengue risk related to CP-La Niña, with 26 locations in Brazil and nine locations in mainland China reducing by over 30% (figure 3C). Results of supplementary analysis indicated the robustness of the main findings (appendix pp 15–21).

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See Online for appendix

For the **Hadley Centre Sea Ice and Sea Surface Temperature dataset** see https://www.metoffice.gov.uk/hadobs/hadisst/

For the **fifth-generation ECMWF reanalysis dataset** see https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means

For **WorldPop** see https://www.worldpop.org

For **DAMIP** see http://damip.lbl.gov

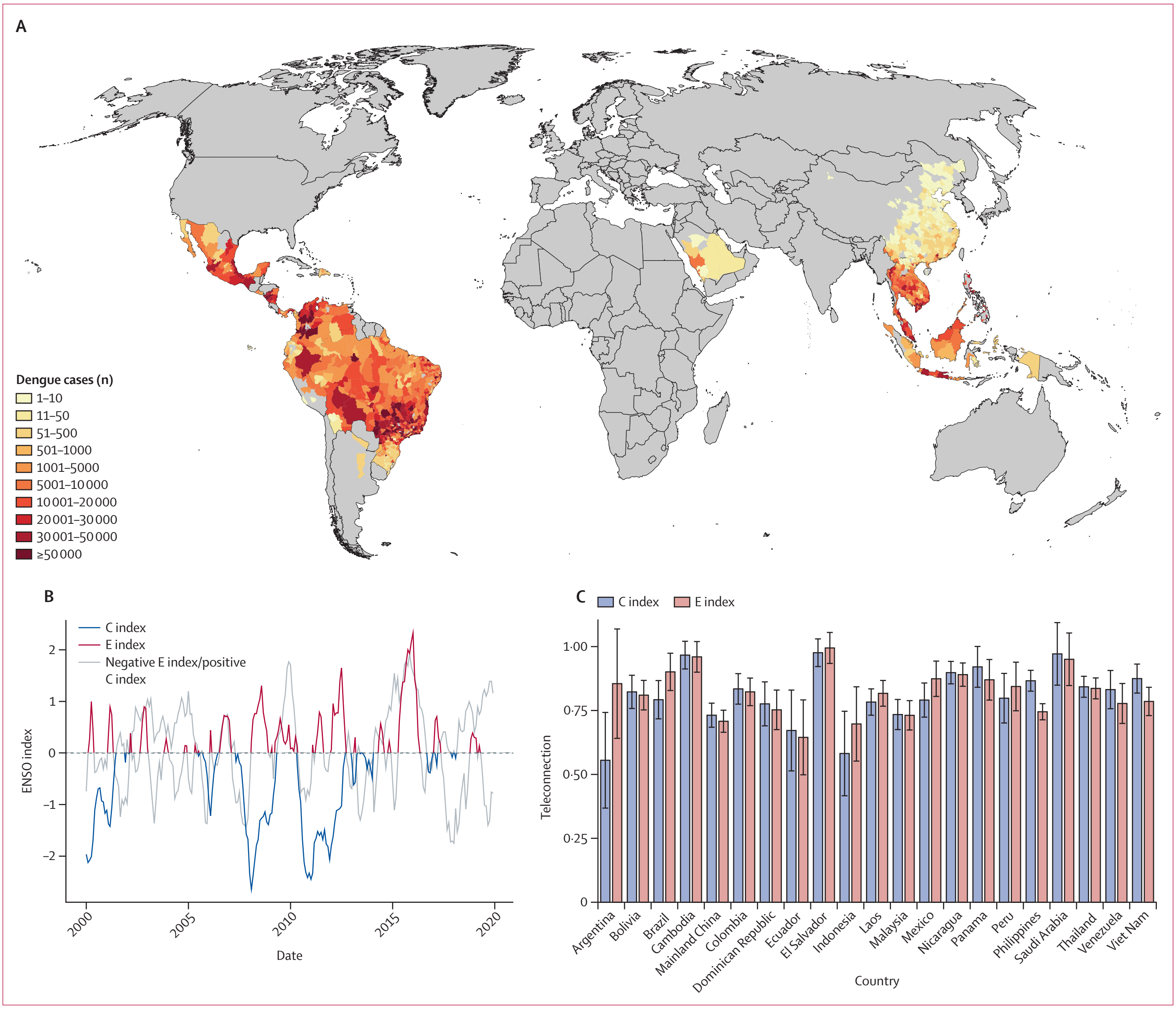


Figure 1: **ENSO index and its teleconnection across 1237 locations in 21 countries during 2000–19**
(A) Spatial distribution of locations and dengue cases of the 1237 locations included in the analysis. (B) Monthly average E and C index during 2000–19 across 1237 locations. The red and blue lines represent the continuous Eastern Pacific (E index >0) and Central Pacific (C index <0) modes, respectively, while the grey lines denote the complementary continuous phases (negative E index and positive C index) to illustrate the full spectrum of variability. (C) Average E index and C index teleconnection during 2000–19 in 21 countries. ENSO=El Niño–Southern Oscillation.

Overall, 4·45% (95% eCI 3·75 to 5·32) and –3·34% (–4·01 to –2·64) of dengue cases were attributable to EP-El Niño and CP-La Niña strengths, respectively (figure 4). The highest EP-El Niño-related AFs of dengue cases were found in Brazil (5·64% [4·70 to 6·81]) and Indonesia (4·56% [3·98 to 5·21]), while the Philippines and Panama exhibited negative values (figure 4A, appendix p 36). CP-La Niña-related AFs showed opposite patterns for most countries (figure 4B, appendix p 37).

As shown in figure 4C and 4D, ACC could explain 48·64% (95% eCI 38·01 to 60·19) of EP-El Niño-attributable increment and 33·05% (28·66 to 38·25) of CP-La Niña-attributable reduction in dengue cases. These estimates corresponded to an excess of 403 197 (95% eCI 315 109 to 498 940) dengue cases and a reduction of 205 641 (178 329 to 238 030) dengue cases across 1237 locations, respectively (appendix pp 34–37). Aggregated results indicated that the proportion of the EP-El Niño strength-related increased dengue burden explainable by ACC was higher for countries in southeast Asia, central America, and South America than others, with the highest observed in Cambodia (54·03% [40·89 to 67·04])

	Dengue cases, n (%)	Spatial resolution	Data period	Locations, n	Region
Argentina	1241 (0·01%)	Subnational	2004–19	3	South America
Bolivia	150 040 (0·80%)	Subnational	2004–19	9	South America
Brazil	13 303 773 (70·56%)	Microregion	2012–19	545	South America
Cambodia	146 403 (0·78%)	Subnational	2000–10	24	Southeast Asia
Mainland China	92 437 (0·49%)	City	2005–19	255	East Asia
Colombia	995 555 (5·28%)	Subnational	2007–19	32	South America
Dominican Republic	31 098 (0·16%)	Subnational	2006–13	32	Caribbean and central America
Ecuador	8 063 (0·04%)	Subnational	2013–19	18	South America
El Salvador	41 958 (0·22%)	Subnational	2000–09	14	Caribbean and central America
Indonesia	182 874 (0·97%)	Subnational	2004–06	24	Southeast Asia
Laos	89 822 (0·48%)	Subnational	2000–10	15	Southeast Asia
Malaysia	257 284 (1·36%)	Subnational	2000–10	10	Southeast Asia
Mexico	339 033 (1·80%)	Subnational	2002–19	31	North America
Nicaragua	700 088 (3·71%)	Subnational	2000–19	17	Caribbean and central America
Panama	107 013 (0·57%)	Subnational	2004–19	11	Caribbean and central America
Peru	85 407 (0·45%)	Subnational	2006–13	14	South America
Philippines	463 078 (2·46%)	Subnational	2000–10	17	Southeast Asia
Saudi Arabia	7018 (0·04%)	Subnational	2018–19	9	West Asia
Thailand	862 747 (4·58%)	Subnational	2000–19	77	Southeast Asia
Venezuela	202 578 (1·07%)	Subnational	2000–05	21	South America
Viet Nam	785 833 (4·17%)	Subnational	2000–10	59	Southeast Asia
Total	18 853 343 (100%)	Microregion, city, subnational	2000–19	1237	Total

***Table:* Summary of the dengue data for 1237 locations in 21 countries during 2000–19**

and Thailand (51·97% [37·81 to 69·03]). For CP-La Niña strength-related reduced dengue burden, the highest proportions explainable by ACC were observed in southeast and west Asia, such as Saudi Arabia (43·10% [30·97 to 56·87]) and Laos (41·76% [32·62 to 51·18]). Location-specific results of dengue burden attributable to ENSO and proportions explainable by ACC are provided in the appendix (pp 22–29).

Discussion

In this study, we assessed the global dengue burden related to EP and CP ENSO strengths across 1237 locations and the contribution of ACC. Our findings suggested that EP-El Niño and CP-La Niña strengths were significantly associated with increased and decreased dengue risks, respectively. Moreover, ACC significantly amplified these impacts, explaining nearly half of the EP-El Niño-attributable case increment and one-third of the CP-La Niña-related reduction. Geographically, the magnitude of this contribution was particularly high in locations or countries of southeast Asia, central America, and South America. The findings provide novel evidence about the role of ENSO on dengue in the context of ACC.

Previously, several studies have explored the relationship between ENSO and risk of dengue incidence, which were consistent with our findings. For example, a global study found that the Oceanic Niño Index (representing the 3-month running mean of SST anomalies in the Niño 3·4 region) was positively associated with the global risk of dengue outbreaks, with a correlation coefficient of 0·52.[5] Meanwhile, evidence from Sri Lanka indicated that El Niño events were significantly associated with increased Aedes vector indices (premise and Breteau index).[4] Additionally, a study conducted in Colombia observed that El Niño (La Niña) events were associated with an increase (decrease) in dengue cases.[17] It is worth noting that existing evidence primarily focuses on dengue and ENSO indicators at a coarse scale, which limits the ability to accurately capture EP-El Niño and CP-La Niña strengths and their regional heterogeneities in meteorological teleconnection. Therefore, our study added to the evidence base of risk assessment with a large sample size covering multiple countries and fine ENSO exposure estimates.

The underlying biological mechanisms explaining the ENSO–dengue association remain conjectural. However, ENSO is speculated to be linked to dengue risk through pathways involving changes in temperature, precipitation, and humidity.[7,18] For example, higher temperatures related to El Niño could lead to more rapid development in mosquito larvae.[10] Some studies suggest that the average gonotrophic cycle (time from blood feeding to oviposition) shortens from 7 days at 24°C to 5 days at 30°C, thereby increasing mosquito biting activity and dengue transmission.[4,19] Changes in precipitation and other hydrometeorological patterns also play crucial roles: El Niño can cause drought in some regions and excessive rainfall in others.[7] Drought in humid regions can lead to increased water storage, creating breeding sites for container-breeders, while heavy rainfall in arid regions generates

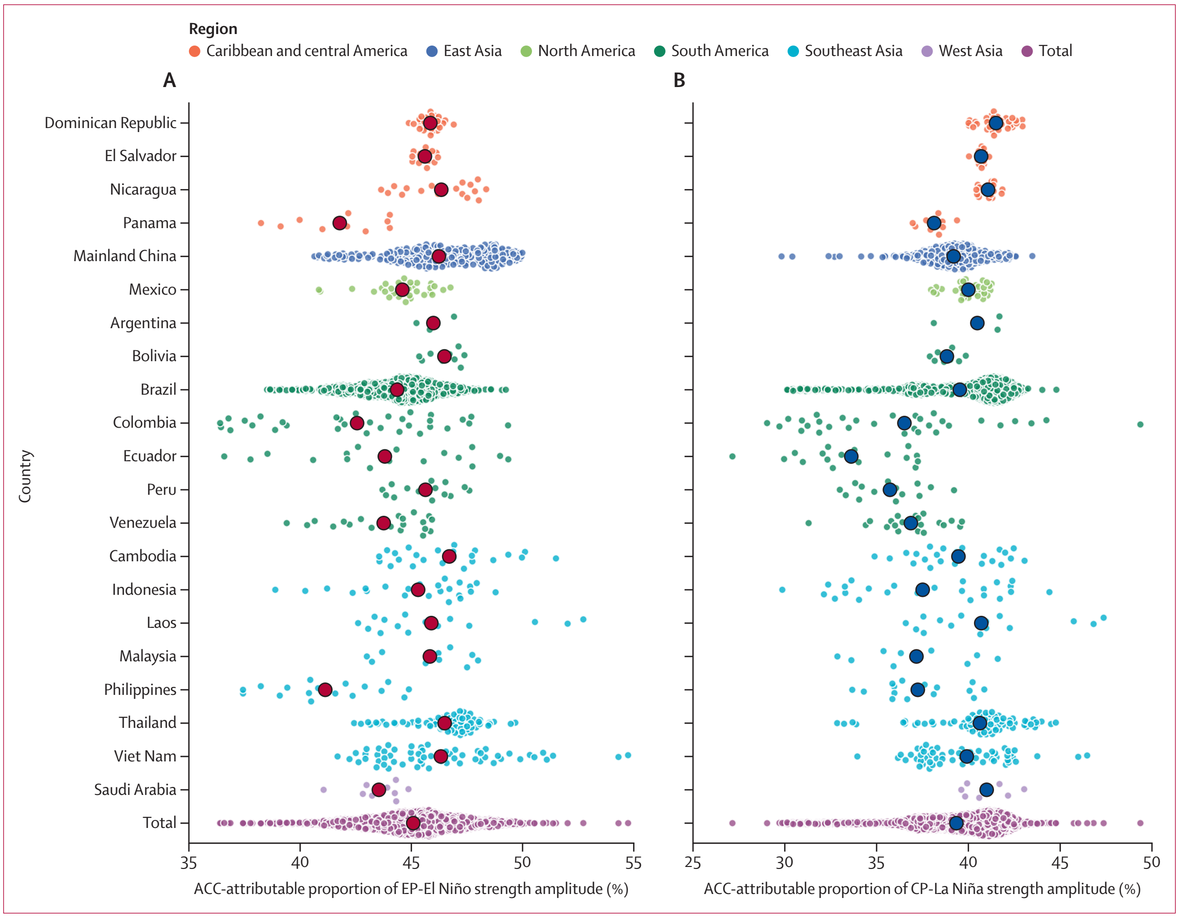


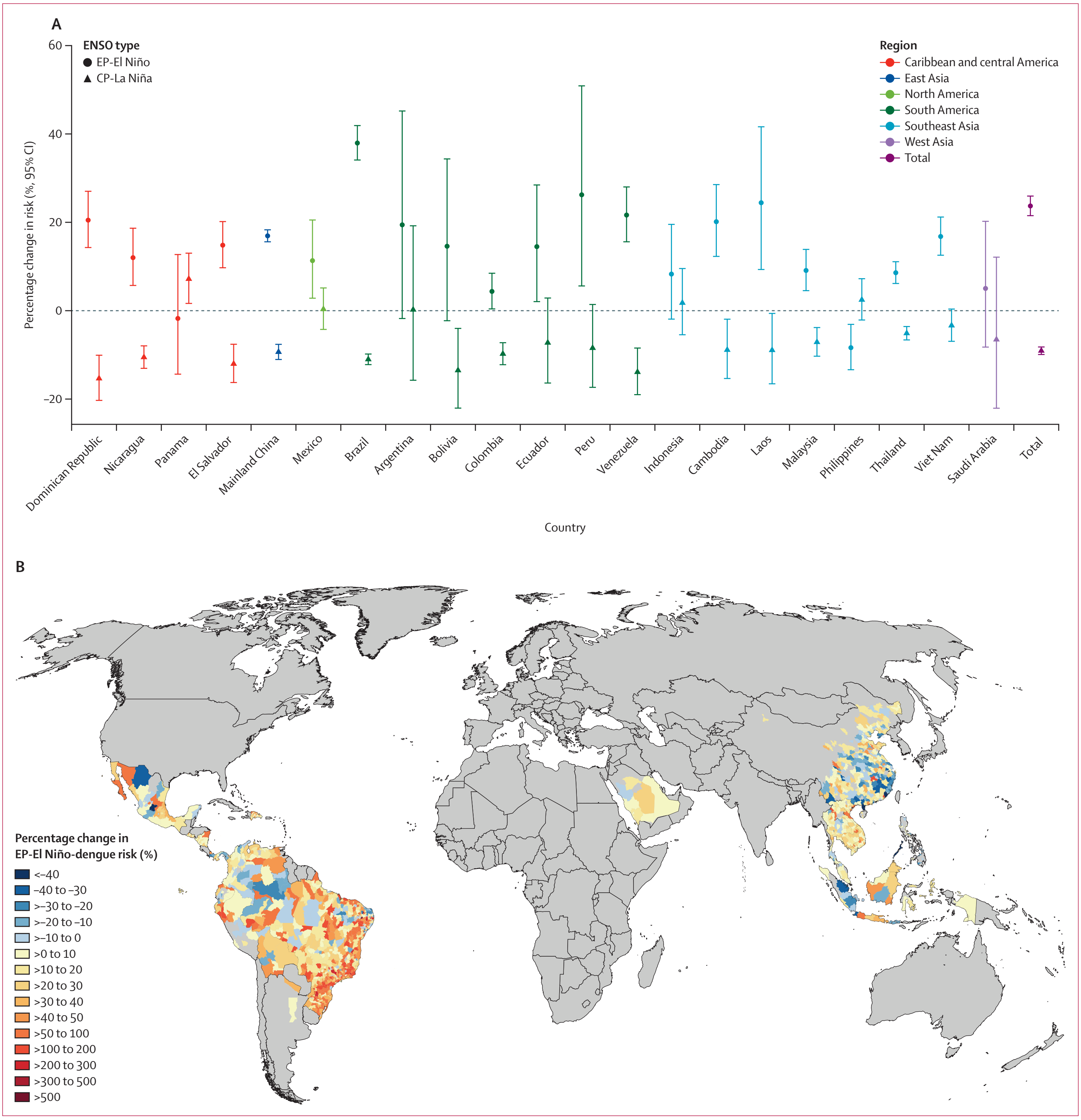
Figure 2: **Proportion of ENSO strength amplitude attributable to ACC**
(A) Proportion of EP-El Niño strength amplitude attributable to ACC during the study period in 21 countries. (B) Proportion of CP-La Niña strength amplitude attributable to ACC during the study period in 21 countries. ENSO=El Niño–Southern Oscillation. ACC=anthropogenic climate change. EP=Eastern Pacific. CP=Central Pacific.

more puddles with a similar effect.[20] In addition, previous studies suggest that El Niño is linked to global economic decline (trillions of US dollars in losses),[8] resulting in inadequate health-care services and weakened vector control efforts in households and communities,[21,22] thereby further increasing the risk of dengue.

In contrast, several studies have suggested that the weather patterns of La Niña are opposite to those of El Niño,[8,23] which might explain its negative association with dengue cases. For instance, compared with El Niño, La Niña is typically characterised by cool global temperatures and a distinct redistribution of precipitation patterns,[10] which might reduce vector density, thereby lowering the transmission potential of dengue.[17] Furthermore, the finding of opposite effects for El Niño and La Niña reflects the fundamental oscillating nature of the ENSO phenomenon.[6,7] As the cold phase of the ENSO cycle, La Niña exhibits ocean–atmospheric anomalies (eg, sea surface cooling and trade wind strengthening) that are physically inverse to the warm phase of El Niño.[6] This climatological antiphase relationship dictates a divergent biological response, thereby driving the opposing dengue risk patterns observed in our results.

This study revealed that ACC exacerbated both the effects of EP-El Niño and CP-La Niña on dengue cases in the majority of locations. Although direct epidemiological evidence quantifying this specific connection remains limited, our results align with growing climatological evidence regarding the influence of ACC.[9,14,16,24] For example, the ocean–atmosphere background altered by ACC could thermodynamically amplify ENSO-driven hydrometeorological anomalies, such as intensified heatwaves and precipitation extremes.[13,14,24] Mechanistically, these meteorological alterations are speculated to shorten the viral extrinsic incubation period and expand larval breeding habitats,[25,26] thereby increasing the magnitude of dengue outbreaks. Therefore, implementing adaptation strategies that account for these amplified climatic impacts remains crucial for reducing the global burden of dengue.

This study unlocks spatial heterogeneity in ENSO-related dengue burden attributable to ACC. Overall, the largest burden was observed in tropical regions of southeast Asia,



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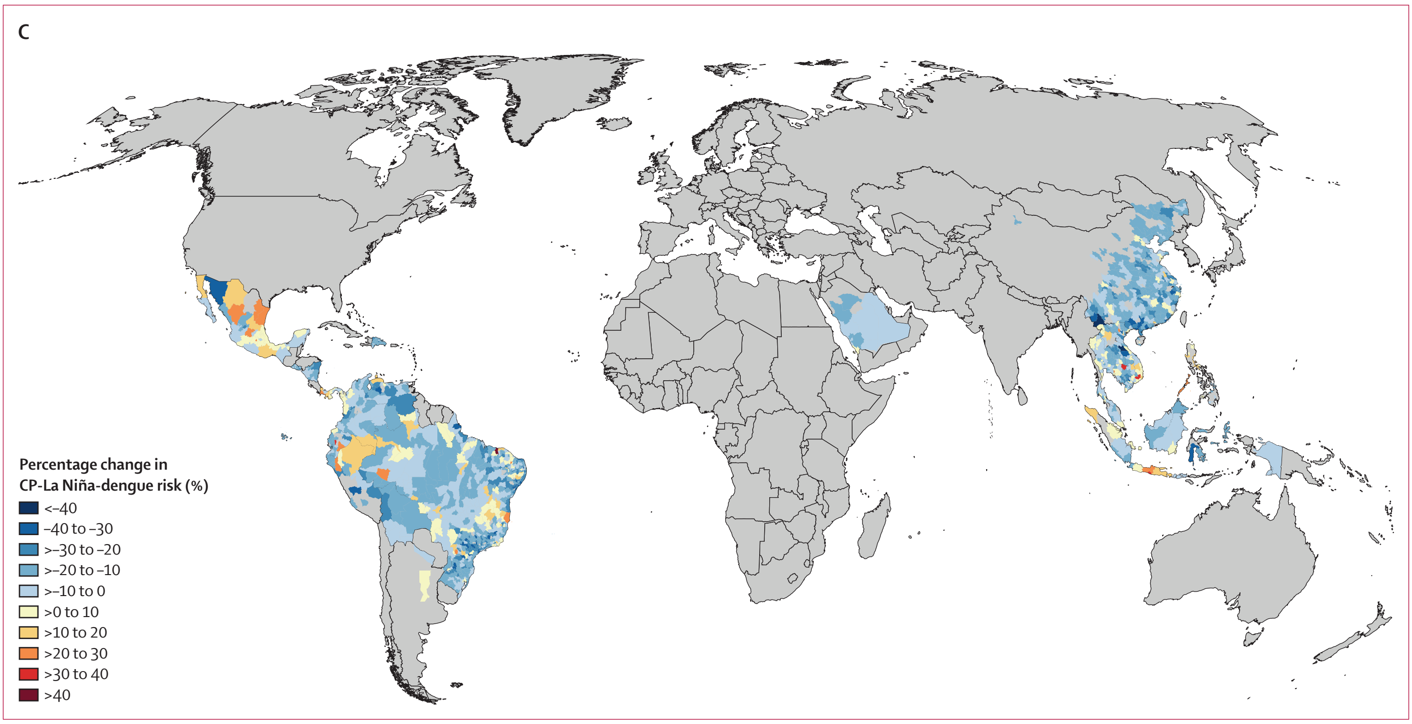
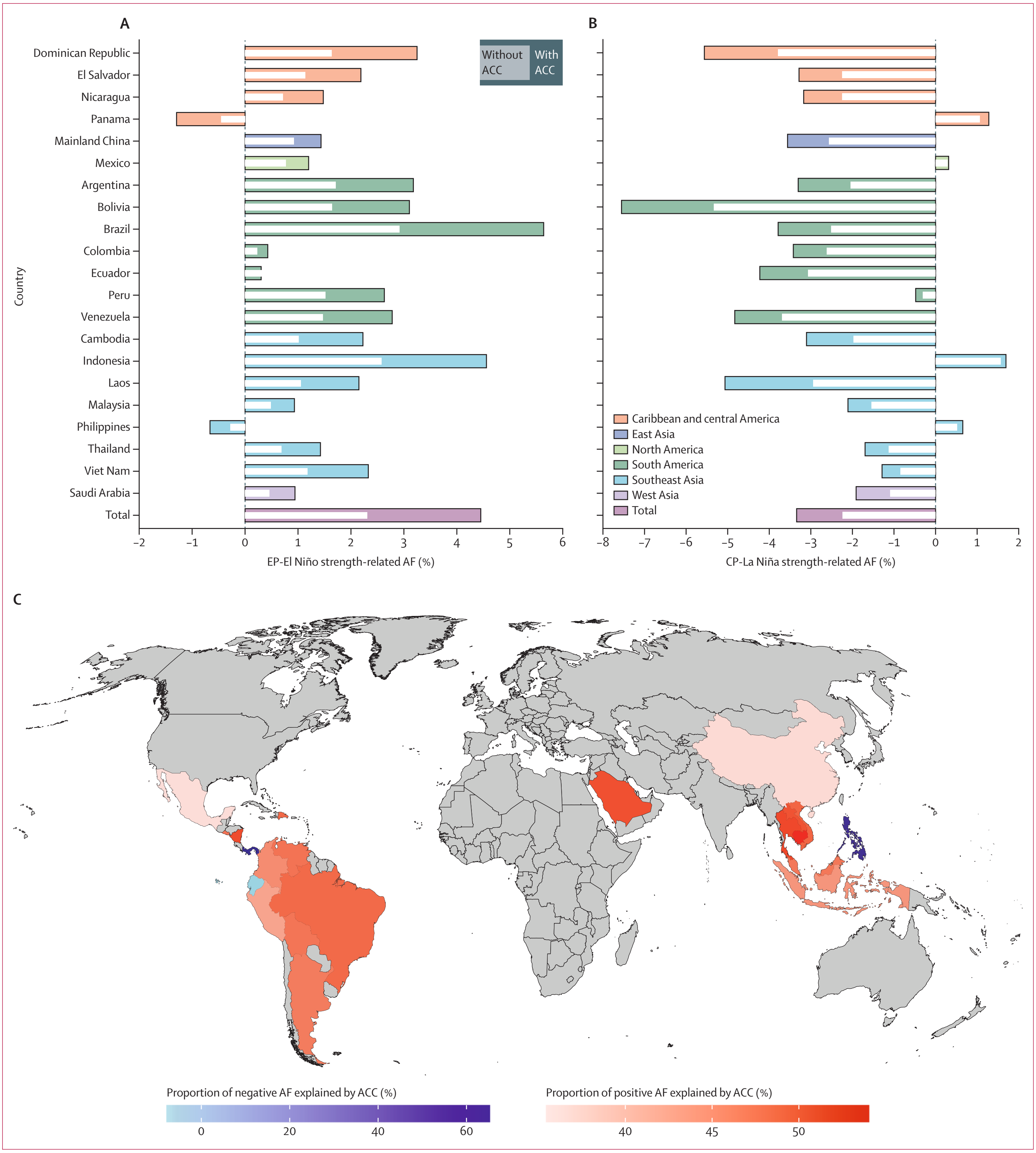


Figure 3: **Estimates of ENSO strength-related dengue risk during 2000–19**
Figure shows percentage changes in dengue risk for each standard deviation increase in EP-El Niño and CP-La Niña strengths. (A) ENSO strength-related dengue associations in 21 countries. (B) EP-El Niño strength-related dengue associations in the 1237 locations (estimates are represented by the location-specific BLUPs). (C) CP-La Niña strength-related dengue associations in the 1237 locations (estimates are represented by the location-specific BLUPs). ENSO=El Niño–Southern Oscillation. EP=Eastern Pacific. CP=Central Pacific. BLUP=best linear unbiased prediction.

central America, and South America. Tropical regions exhibit ideal conditions for dengue transmission (eg, high temperature and humidity) and strong climatic responses to ENSO events,[20,27] making them possibly more susceptible to ACC and amplified ENSO-related dengue burden. In addition, limited surveillance and health-care infrastructure corresponds with underdeveloped prevention frameworks in several low-income southeast Asian countries,[25] exacerbating climate vulnerability. However, the Philippines and Panama showed opposite patterns. These exceptions could be explained by differences in baseline ENSO–dengue associations. For example, hydroclimatological assessments indicate that El Niño events drive pronounced precipitation deficits in the Panama Canal watershed and widespread drought conditions characterised by below-normal rainfall across the Philippines.[28,29] These moisture-limited environments likely reduce the availability of rain-dependent larval habitats, thereby suppressing vector population growth and dengue transmission despite the presence of favourable warmer temperatures.

This spatial heterogeneity highlights a profound climate inequity: the burden of ENSO-related dengue attributable to ACC is disproportionately concentrated in tropical low-income and middle-income countries. These regions face the gravest health consequences due to the intersection of high climatic suitability and constrained adaptive capacity.[25] This vulnerability is significantly exacerbated by the persistent negative effects of El Niño on economic growth,[8] which can strain public health resources and infrastructure essential for effective vector control. Moreover, the rising complexity of infectious disease dynamics in an era of global change suggests that current health systems remain fragile against compounding environmental shocks.[22] Consequently, intergovernmental actions are encouraged to prioritise directing support towards building climate-resilient health systems in these hotspots to address the amplifying effects of ENSO variability, thereby reducing the substantial global economic and health burden of dengue.

This study has several key strengths. To our best knowledge, this is the first study to quantify ENSO-related dengue burden attributable to ACC on a multicountry scale. Unlike isolated studies, this study applied a unified analytical framework across 1237 locations to quantify the spatial heterogeneity in ENSO effect (eg, opposite patterns in southeast Asia *vs* South America). Therefore, our findings can inform adaptation strategies at various governmental levels. In addition, this study used a continuous ENSO strength metric that integrates global indices with local teleconnections, offering a more precise quantification of local climatic forcing than



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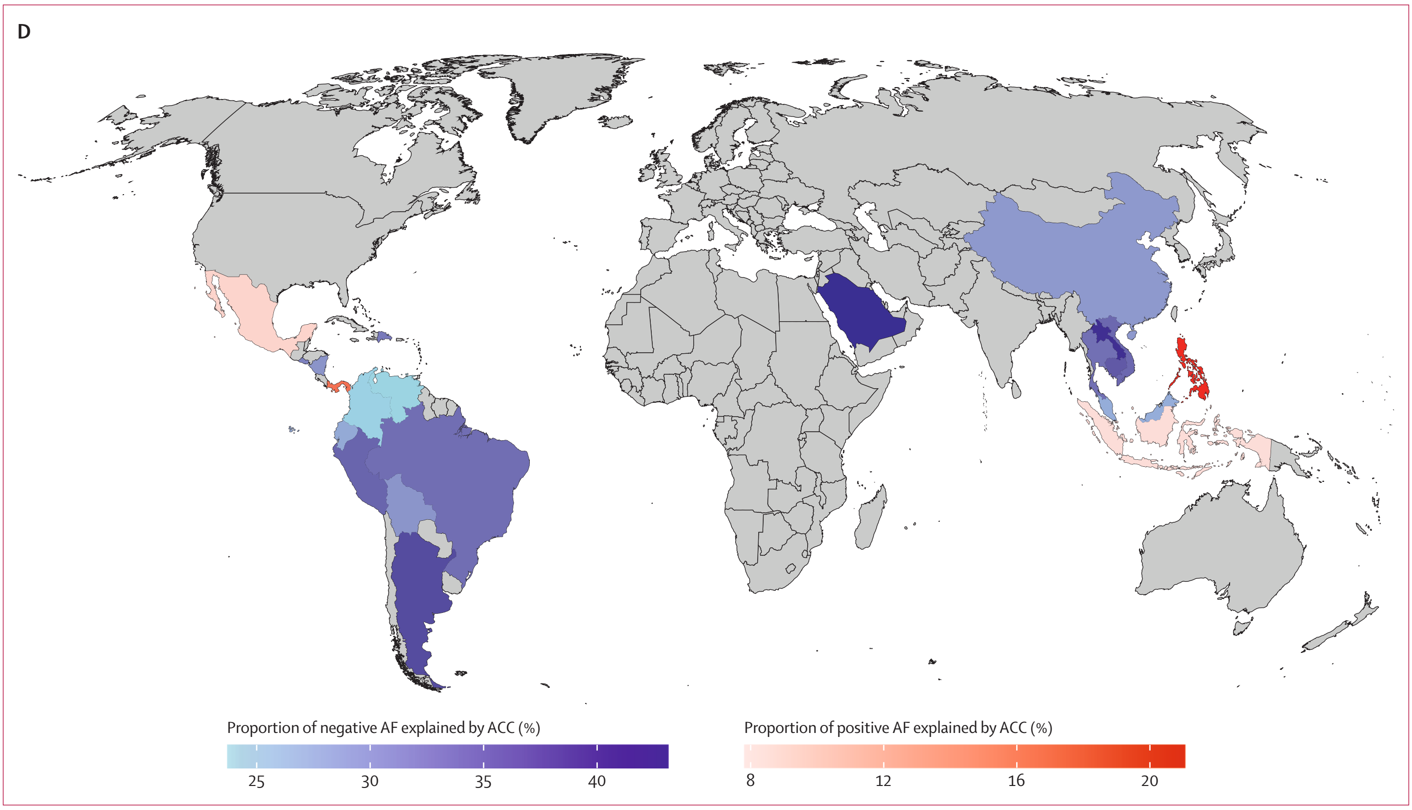

Figure 4: **ENSO-related dengue burden attributable to ACC**
(A, B) AF of total dengue cases associated with EP-El Niño (A) and CP-La Niña (B) strength across 21 countries. For each country, the paired bars represent the estimated AF under two climate scenarios: the factual scenario (with ACC) and the counterfactual scenario (without ACC). (C, D) Proportion of the ENSO-related dengue cases attributable to ACC for EP-El Niño (C) and CP-La Niña (D) strength across 21 countries. For each country, the value is calculated as the difference between the factual and counterfactual scenarios divided by the factual estimate. Red shades indicate the proportion of the increased dengue burden (positive AF) attributable to ACC, whereas blue shades indicate the proportion of the reduced dengue burden (negative AF) attributable to ACC. ENSO=El Niño–Southern Oscillation. ACC=anthropogenic climate change. AF=attributable fraction. EP=Eastern Pacific. CP=Central Pacific.

traditional binary classifications. This approach provides a standardised insight unattainable by fragmented local studies.

Limitations of this study should also be acknowledged. Despite the wide spatial and temporal scope, we were unable to include all regions (eg, parts of Africa and North America) or data before 2000 (capturing a relatively limited number of ENSO events), and the surveillance data used might be subject to reporting biases and inconsistent case definitions. Due to the lack of high-resolution global longitudinal data, our model did not explicitly account for non-climatic drivers including population immunity, serotype switching, urbanisation, vector control, human movement, and detailed demographics, which could introduce residual confounding. Additionally, we characterised EP-ENSO and CP-ENSO strength using a composite metric of temperature and precipitation teleconnections to capture aggregate climatic sensitivity. Although this simplifies individual meteorological pathways, sensitivity analyses confirmed the robustness of this integrated approach. We assumed stationarity in ENSO patterns to ensure the statistical robustness of our findings, while climate change also drives non-stationary ENSO changes. For example, climatological evidence indicates that greenhouse warming will lead to an increased frequency of extreme ENSO events, a non-linear amplification of their amplitude, and an eastward shift of the ENSO anomaly centre.[9,14,24,30] By holding these dynamics constant, our approach potentially underestimates the dengue burden attributable to ACC. Future studies should focus on quantifying the disease burden driven by more frequent extreme ENSO events and their spatial shifts.

In conclusion, ENSO was associated with risk of dengue across countries worldwide, with a key contribution of ACC to the related disease burden identified. The spatial heterogeneity in ENSO's effect and the substantial contribution of ACC call for action from local and intergovernmental policy makers to design strong, region-specific adaptation strategies to alleviate the current and future dengue burden in the context of climate change.

Contributors

GL, QZ, BL, and WM conceived and designed the study. PL, PW, AU, ST, NR, FS, MLB, DR, KLE, and AW provided critical input on methodology, visualisation, data interpretation, and manuscript revision. MG, WL, YY, XZ, and QL curated and processed the data and conducted the formal analysis. AU, DR, PL, MG, QZ, and WM contributed to funding acquisition. GL drafted the manuscript. QZ, BL, and WM supervised the study. All authors read and approved the final version of the manuscript. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication. GL, QZ, BL, and WM accessed and verified the underlying data.

Declaration of interests

We declare no competing interests.

Data sharing

Dengue case data from countries other than Brazil and mainland China are available in the public domain through the cited sources. Code sources and additional processed data are available from the corresponding author upon reasonable request.

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