Climate Vulnerability and Sea-Level Rise: An Interactive Analysis

An interactive exploration of socioeconomic and climate stressors across Bangladesh, Maldives, and the Philippines, including sea-level rise, flood exposure, and migration patterns.

AUTHOR
Mandy Sun, Alivia Castor, Jaden Wang, Yubo Xing

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1. Introduction

This project explores **Climate Vulnerability and Urban Expansion** in three of Asia's countris with the most at-risk coastal cities: **Bangladesh**, **Maldives**, and **Philippines**.

Our motivation for this project stems from growing concerns about the future of cities like Dhaka, Malé, and Manila in the face of rising sea levels, increased flooding, and rapid urbanization.

We aim to analyze how rapid urbanization intersects with climate change impacts — focusing on urban growth patterns, climate vulnerabilities, infrastructure risks, and migration trends.

Understanding these interactions is critical for informing urban planning, climate adaptation strategies, and building resilience for vulnerable communities.

2. Data Sources

We integrate data from multiple sources to provide a holistic view:

- **Satellite and Sea Level Data:** NASA Earthdata, USGS EarthExplorer.
- **Climate Data:** World Bank Climate Knowledge Portal, PMC Climate Change Studies (Temperature, Precipitation, Sea Level Rise).
- **Socioeconomic and Urban Growth Data:** UN-Habitat Reports, Bangladesh Urban Resilience Report, Maldives Climate Vulnerability Study.

Each dataset contributes information on population growth, climate stressors, and migration — all critical dimensions of climate vulnerability.

See below for the tables of each of the data sources referenced.

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3. Data Cleaning and Preparation

- Standardized country names.

- Reshaped datasets for consistency (e.g., melting precipitation data).
- Handled missing values where necessary.
- Merged datasets by **Country** and **Year** for unified analysis.

At the end of this step, we created a panel dataset combining urbanization indicators, flood exposure, precipitation trends, and socioeconomic metrics.

3.1. Load and Clean All Datasets

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	Year	Sea Level (mm)	Country	Metric
0	1970.5	-71.489826	Bangladesh	Reconstruction Obs
1	1971.5	-56.537595	Bangladesh	Reconstruction Obs
2	1972.5	-122.652400	Bangladesh	Reconstruction Obs
3	1973.5	-59.009730	Bangladesh	Reconstruction Obs
4	1974.5	-52.291594	Bangladesh	Reconstruction Obs

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	Country	Year	Value
0	Bangladesh	1950	2216.83
1	Maldives	1950	1875.74
2	Philippines	1950	2477.81
3	Bangladesh	1951	2204.07
4	Maldives	1951	1847.45

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	Country	Year	Metric
0	Bangladesh	1950	5.05
1	Maldives	1950	0.00
2	Philippines	1950	0.00
3	Bangladesh	1951	4.37
4	Maldives	1951	0.00

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	Country	Year	FloodType	Days
0	Bangladesh	1979	High Tide Flood Days Minor	37
1	Bangladesh	1980	High Tide Flood Days Minor	37

	Country	Year	FloodType	Days
2	Bangladesh	1981	High Tide Flood Days Minor	52
3	Bangladesh	1982	High Tide Flood Days Minor	29
4	Bangladesh	1983	High Tide Flood Days Minor	35

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3.2 Merge Data

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```
Series Name Country Name  Year  GDP (current US$)  Net migration  \
0             Bangladesh  1975       1.944835e+10      -390212.0
1             Bangladesh  1976       1.011711e+10      -424970.0
2             Bangladesh  1977       9.651149e+09      -458491.0
3             Bangladesh  1978       1.328177e+10      -486721.0
4             Bangladesh  1979       1.556548e+10      -507354.0

Series Name  Population, total  Urban population (% of total population)  \
0                   77854351.0                                     9.836
1                   79855318.0                                    10.701
2                   81867264.0                                    11.630
3                   83889655.0                                    12.629
4                   85935072.0                                    13.701

Series Name  Urban population growth (annual %)
0                                     11.127637
1                                     10.966480
2                                     10.813347
3                                     10.681091
4                                     10.556273
    Country Name        Series Name  Year         Value  GrowthRate
23    Bangladesh  GDP (current US$)  1976  1.011711e+10  -47.979575
43    Bangladesh  GDP (current US$)  1977  9.651149e+09   -4.605701
63    Bangladesh  GDP (current US$)  1978  1.328177e+10   37.618502
83    Bangladesh  GDP (current US$)  1979  1.556548e+10   17.194347
103   Bangladesh  GDP (current US$)  1980  1.813805e+10   16.527397
```

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	Country	Year	GDP (current US$)	Net migration	Population, total	Urban population (% of total population)	Urban population growth (annual %)	Sea Level (mm)
0	Bangladesh	1975	1.944835e+10	-390212.0	77854351.0	9.836	11.127637	NaN
1	Bangladesh	1976	1.011711e+10	-424970.0	79855318.0	10.701	10.966480	NaN
2	Bangladesh	1977	9.651149e+09	-458491.0	81867264.0	11.630	10.813347	NaN
3	Bangladesh	1978	1.328177e+10	-486721.0	83889655.0	12.629	10.681091	NaN

	Country	Year	GDP (current US$)	Net migration	Population, total	Urban population (% of total population)	Urban population growth (annual %)	Sea Level (mm)
4	Bangladesh	1979	1.556548e+10	-507354.0	85935072.0	13.701	10.556273	NaN

4. Exploratory Data Analysis (EDA)

4.1 Single Variable Visual Explorations

We use visualizations to examine single-variable trends over time: - Population growth - Sea level rise - Migration patterns - Precipitation changes - Flood event frequencies (Minor, Moderate, Major) - Heat Changes

Interactive visualizations help uncover hidden relationships between climate stressors and urban expansion.

Urban Population Maps

To understand the spatial distribution of urban populations in vulnerable coastal regions, we created interactive bubble maps for Bangladesh, Maldives, and the Philippines. Each bubble's size represents the relative population of a city, providing a visual sense of density, urban concentration, and exposure to coastal risks.

Mapping population centers helps contextualize vulnerability by showing where the greatest number of people — and critical infrastructure — are located relative to rising sea levels, flooding risks, and extreme weather events. This spatial understanding is crucial for assessing potential human impacts and prioritizing adaptation efforts.

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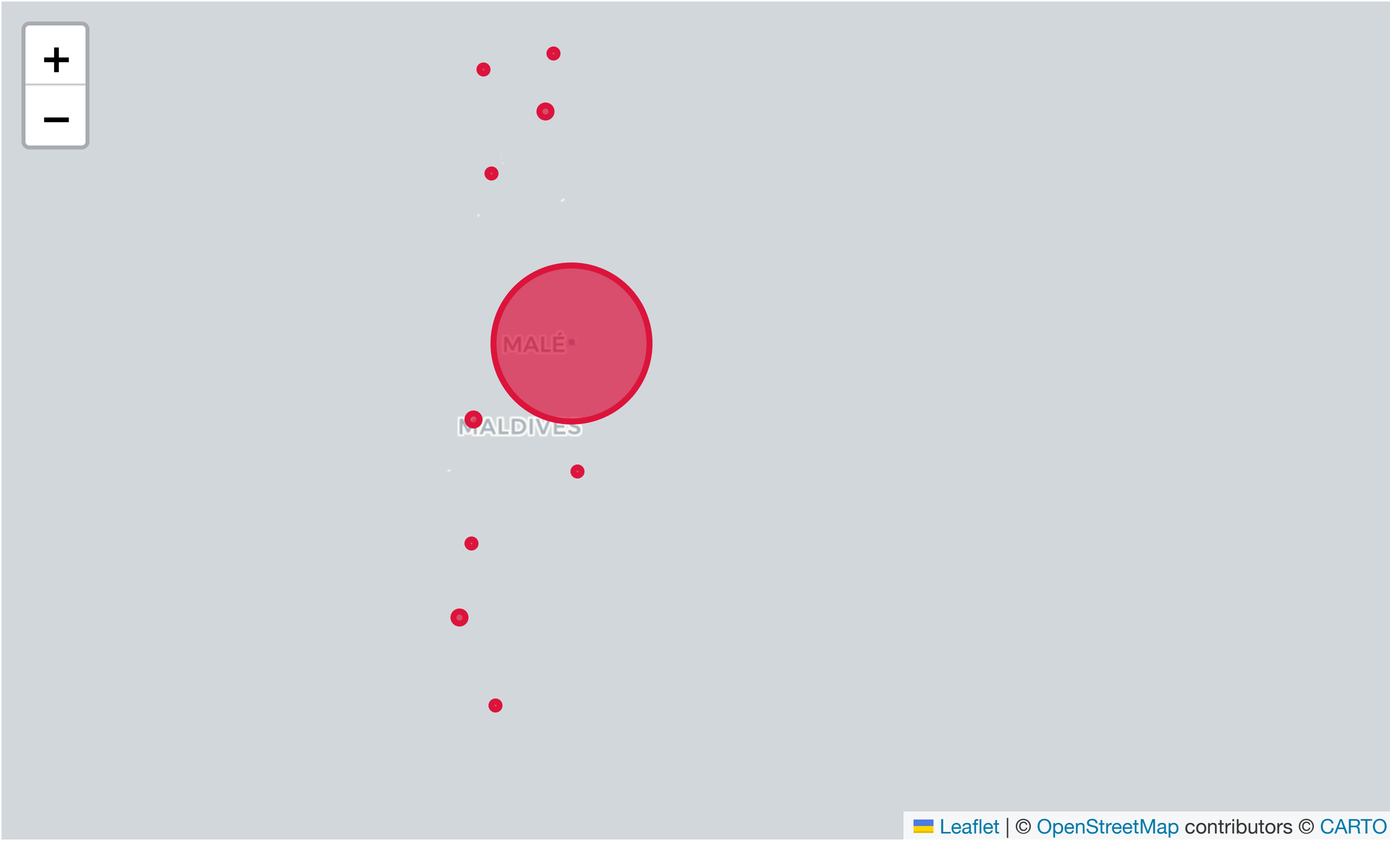

Regional Centers of Interest:

- Malé had by far the highest population concentration, with approximately 133,019 people, highlighting its extreme urban density and exposure to sea level rise.
- Naifaru (4,101 people) and Kudahuvadhoo (3,132 people) also represent significant smaller urban centers.
- It is important to note that in a geographically fragmented country like the Maldives, urban populations are highly clustered on low-lying islands, making them extremely vulnerable to climate impacts.
- Urban concentration increases the stakes: even small amounts of sea level rise or coastal flooding can disproportionately affect a large share of the country's population and infrastructure.
- Adaptation and planning efforts must prioritize densely populated urban hubs like Malé to minimize displacement and economic disruption, without neglecting other islands that are still intimately vulnerable, despite their smaller population.

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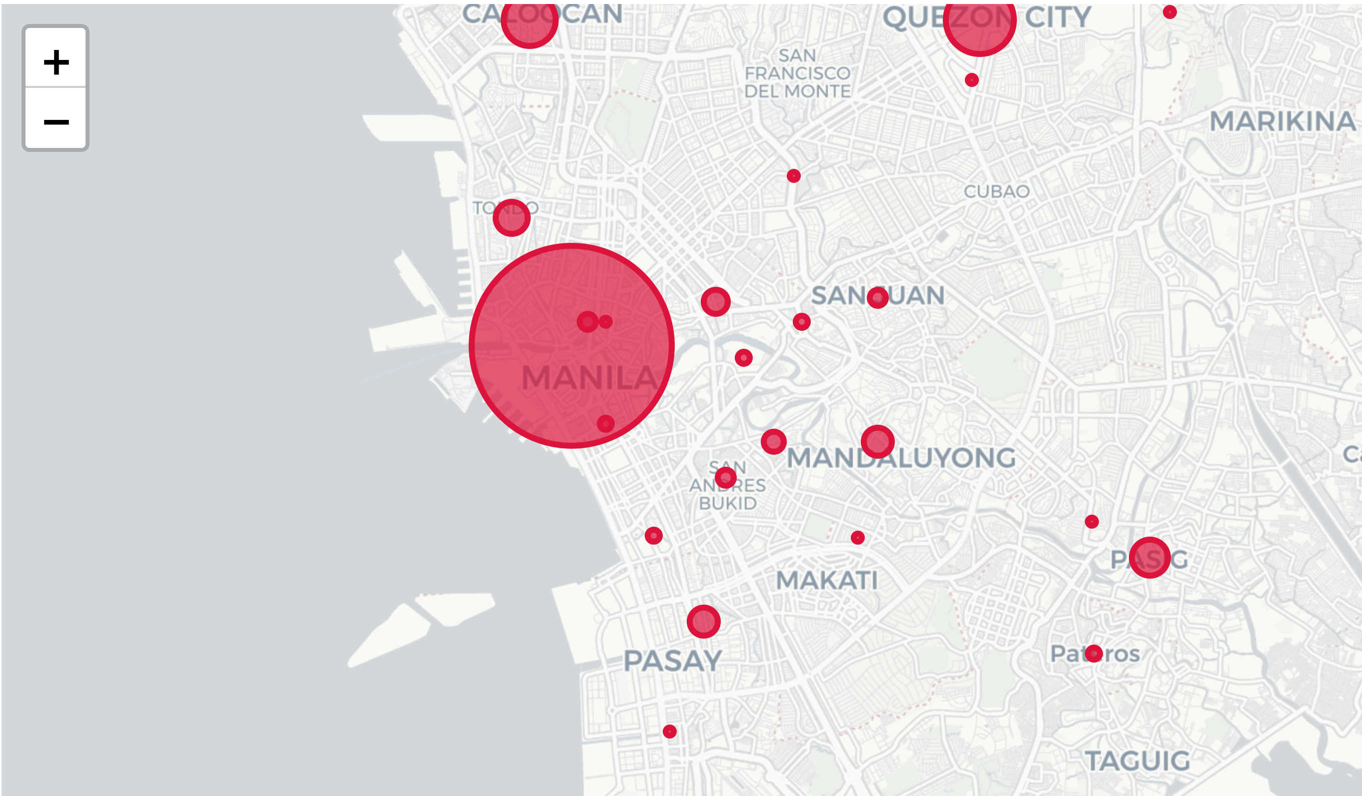

Leaflet | © OpenStreetMap contributors © CARTO

Regional Centers of Interest:

- Metro Manila is overwhelmingly the dominant urban hub — its bubble is massively larger than any other and over 24 million population, signaling extreme concentration.
- Canagatan, Zamboanga, and Davao follow Manila as a relatively large metro center with populations lying around 1-3 million.
- The Philippines' urban and economic risk is highly centralized. Climate shocks (flooding, typhoons, sea-level rise) affecting Metro Manila would have outsized national consequences

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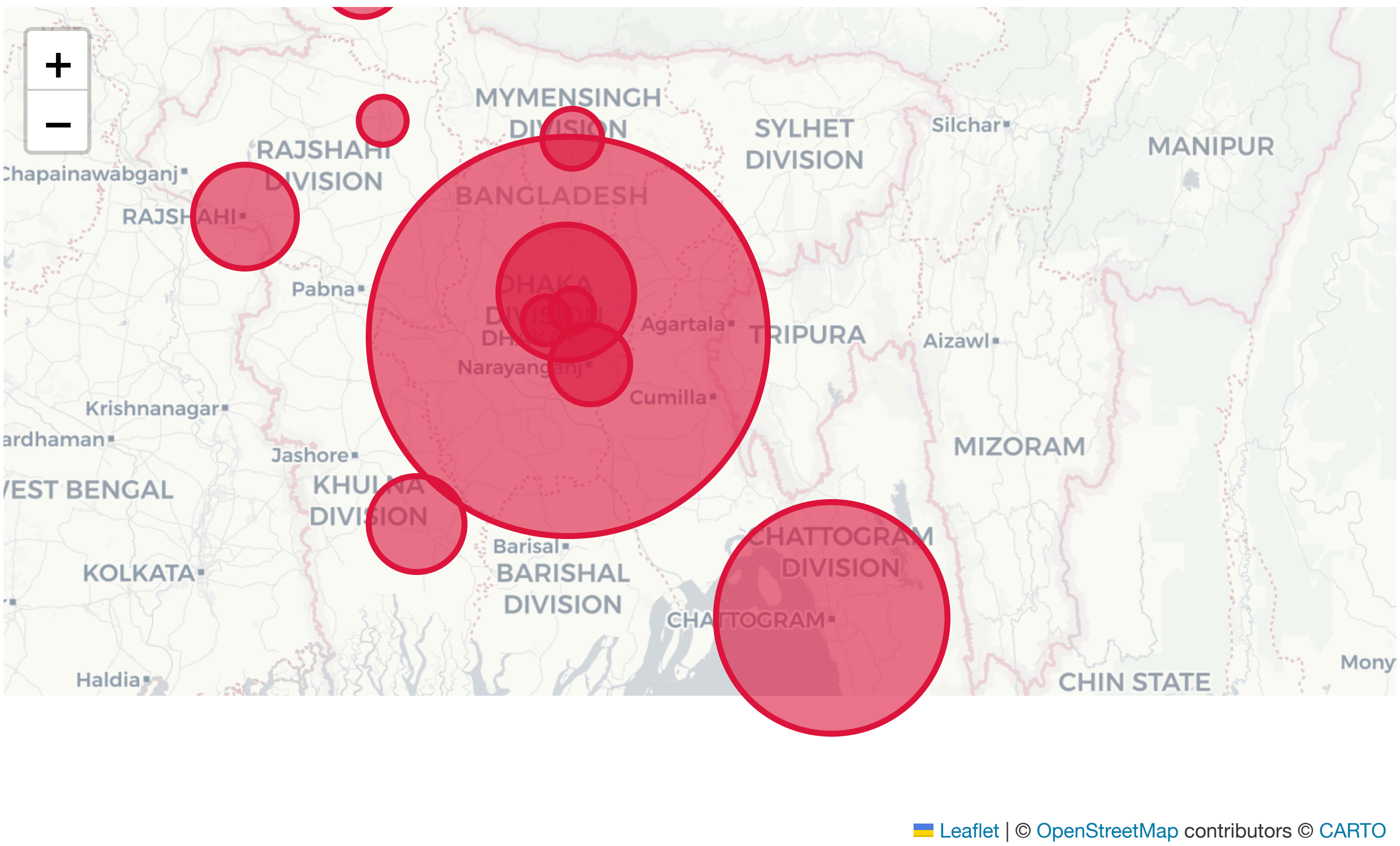

Regional Centers of Interest:

- Dhaka overwhelmingly dominates Bangladesh's urban landscape with 18–19 million people — more than double the next largest city.
- Chattogram, with around 7 million residents, is the second major urban center, and it's also coastal — making it another highly exposed area to sea-level rise and climate hazards.
- Both Dhaka and Chattogram — the two largest cities — are either near major rivers (i.e. Buriganga) or directly coastal, meaning Bangladesh's urban growth is heavily exposed to flooding, storms, and sea-level rise.

Sea Level Trend Visualization

There are two primary methods of capturing sea level data: **reconstruction observations** and **satellite altimetry**.

- **Reconstruction Observations**:
  This method combines historical tide gauge records from coastal stations to estimate past sea level changes. It provides long-term trends dating back to the 19th and early 20th centuries but can be spatially uneven, depending on the availability and distribution of tide gauges.

- **Satellite Altimetry**:
  This method uses satellites equipped with radar altimeters to directly measure the distance between the satellite and the sea surface. Operating since the early 1990s, satellite altimetry offers high-resolution, global coverage of sea level changes, capturing short-term variability and long-term trends with greater precision.

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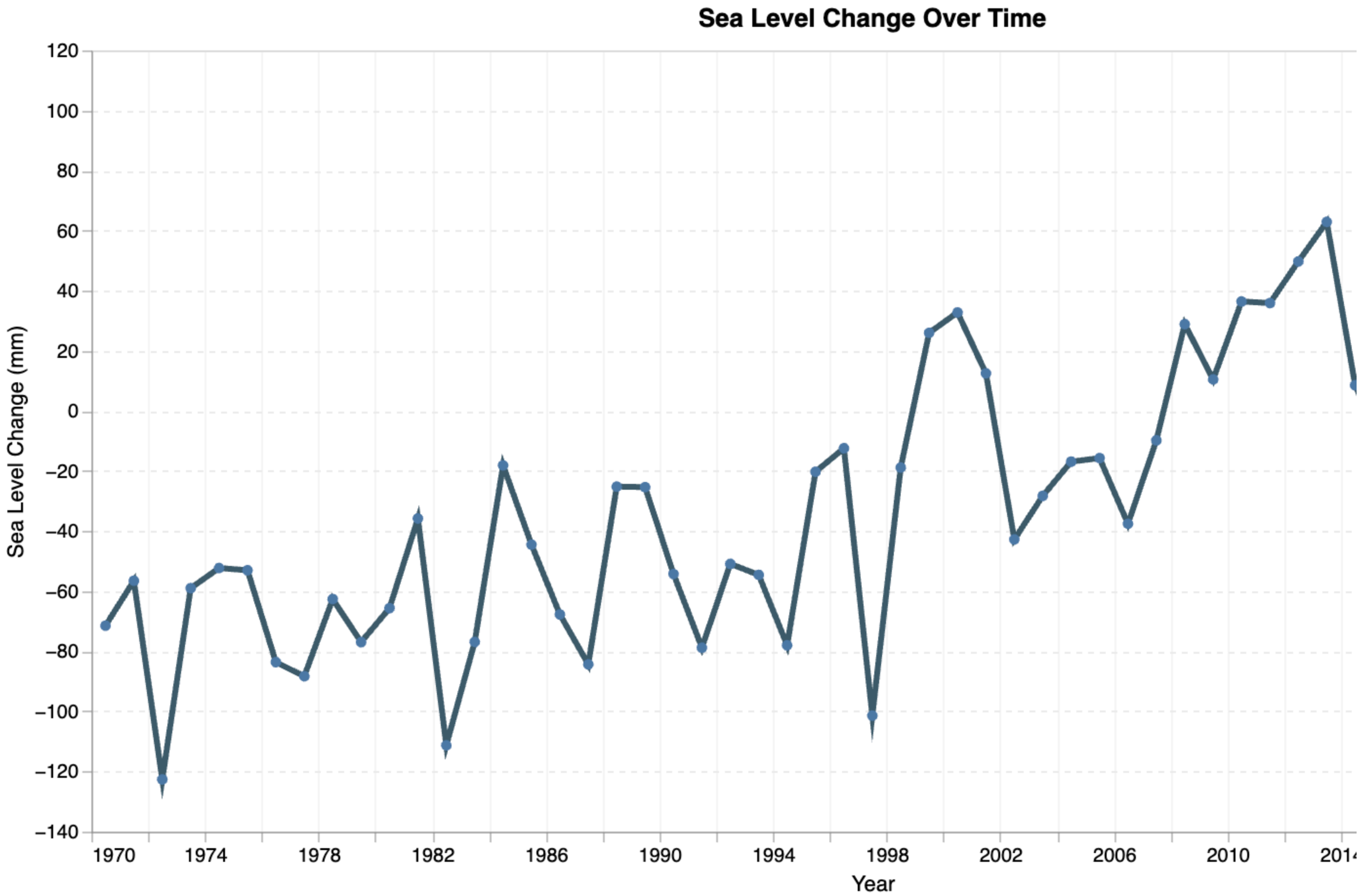

Sea Level Metric: ◉Reconstruction Obs ○Satellite Altimetry

Country: ◉Bangladesh ○Maldives ○Philippines

Observations

- Sea level was consistently negative (below a baseline) until about 2000 for all countries.
- Around 2000, the trend shifts sharply upward, and the sea level crosses into positive territory.
- The sea level change accelerates significantly after 2010, culminating in a sharp rise around 2020–2022.
- for the satelite altimery, the extreme “spikiness” likely represents short-term variations like seasonal changes, storm surges, tides, and monsoon effects, rather than long-term trends. Despite the noise, there’s a general tendency for sea levels to be higher over time (center of oscillations shifts upward).

Extreme Heat Trends

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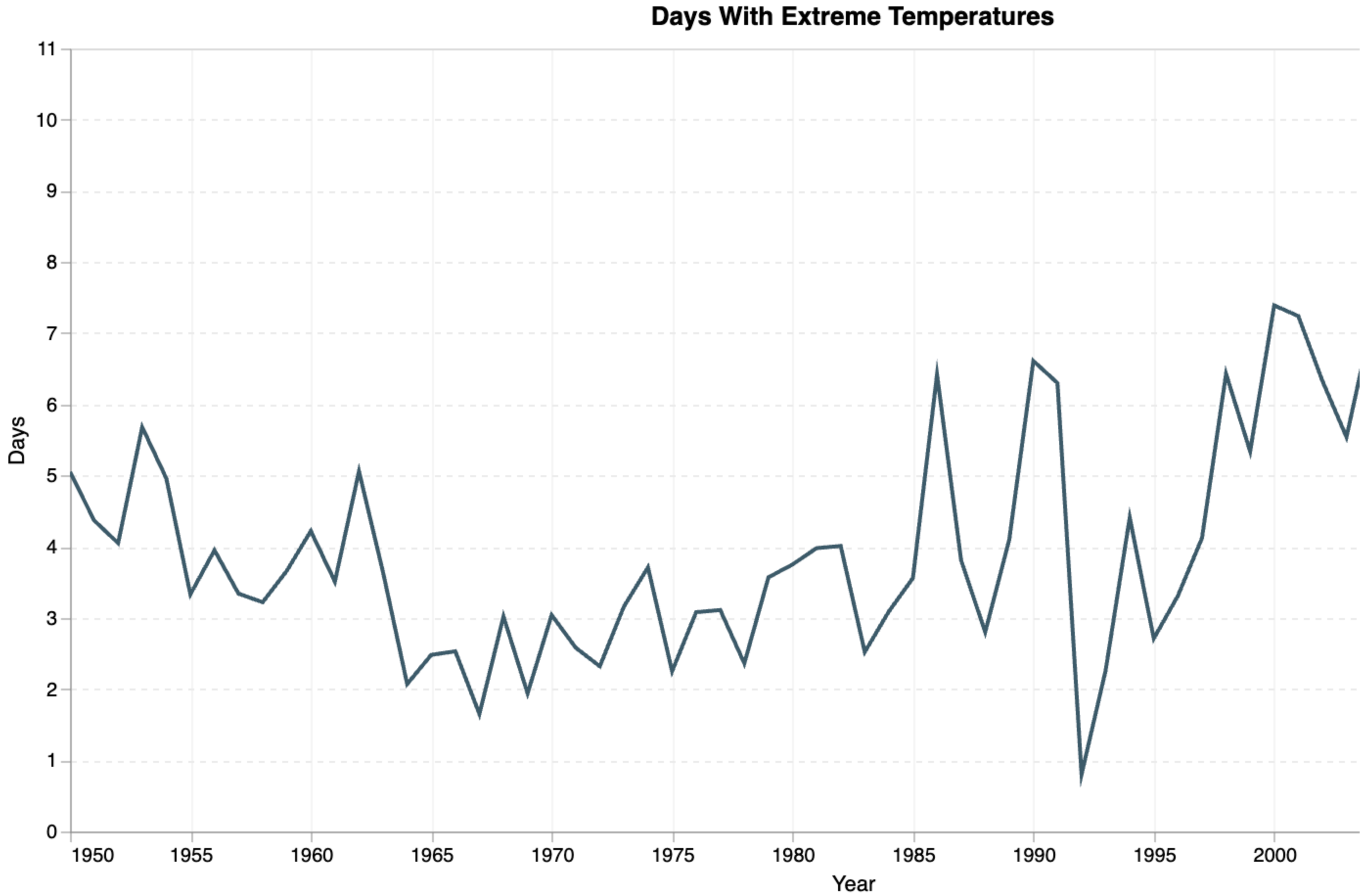

Country: Bangladesh Maldives Philippines

Observations

- Especially after 1990, the number of extreme days in Bangladesh rises much faster.
- Both Maldives and Phillipines exhibit 0 values for heat temperatures.

High Tide Flooding Trends

High tide flooding, often referred to as "nuisance flooding," is categorized into minor, moderate, and major events based on the severity of impacts.

- Minor floods typically cause localized disruptions
- Moderate floods can damage property and critical infrastructure
- Major floods lead to widespread evacuations and significant economic losses.

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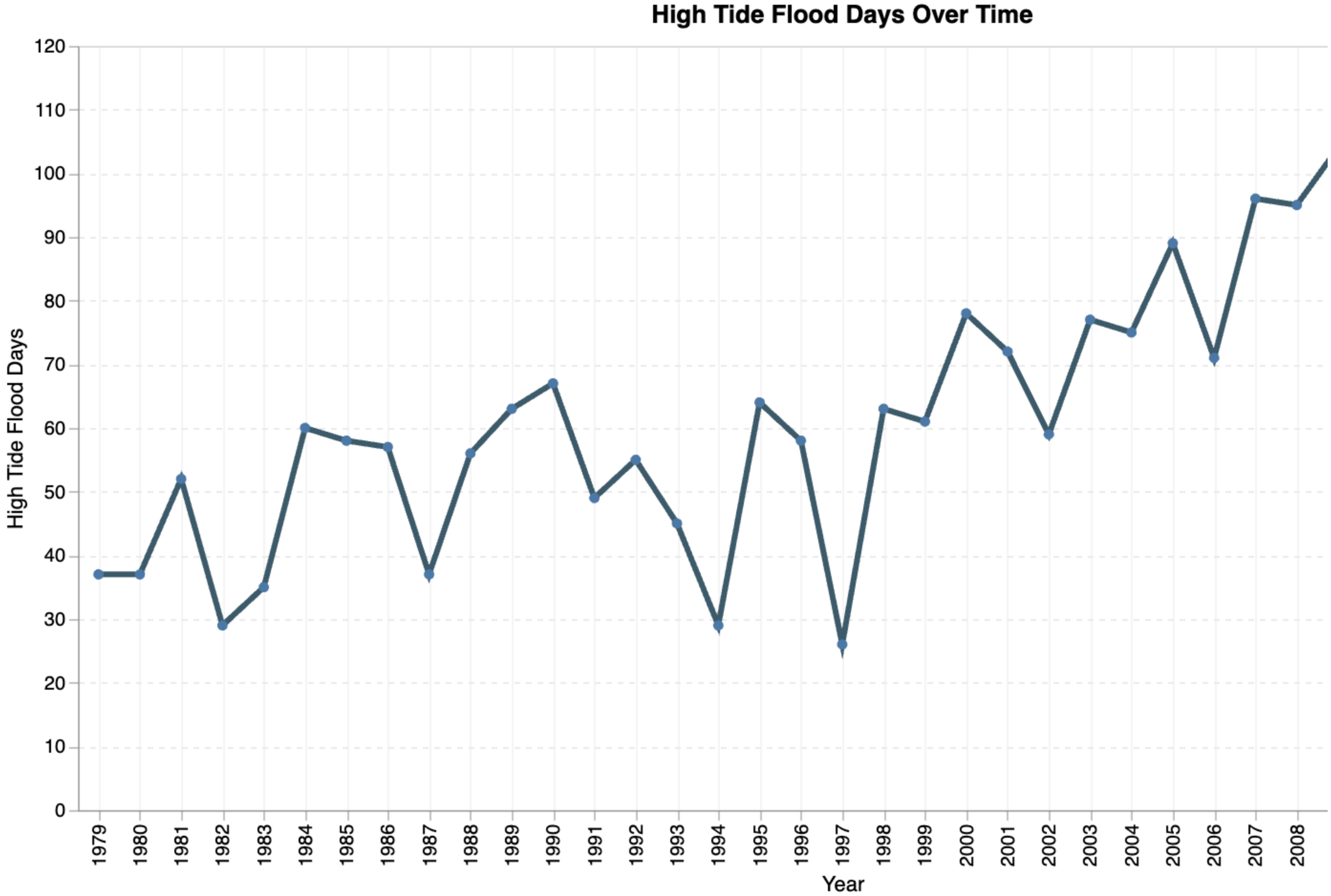

Flood Type: High Tide Flood Days Minor High Tide Flood Days Moderate High Tide Flood Days Majo

Country: Bangladesh Maldives Philippines

Observations

Observations on High Tide Flooding

- **Higher Exposure in Bangladesh**:
  Bangladesh experiences a significantly higher number of major high tide flood days compared to the Philippines, peaking at 13 days in 2009. In contrast, the Philippines' major flood days peaked at just 2 days in 2008.

- **Policy and Infrastructure Responses**:
  The Philippines, situated in the Pacific Ring of Fire and regularly exposed to extreme weather events, has invested heavily in disaster risk reduction. A notable example is the $144 million flood management project launched in 2024, focused on urban drainage improvements, flood barriers, and early warning systems.
  Meanwhile, Bangladesh's approach has been more adaptive, often described as a "living with floods" strategy. Policies emphasize discouraging settlements in high-risk flood zones and promoting the use of water-resistant construction materials and salt-tolerant crops. However, the emphasis remains largely **responsive** rather than **preventive**, reflecting infrastructural and financial constraints.

- **Environmental Trade-offs in Phillipines**:
  Residents in Phillipinse report the loss of native vegetation, particularly mangrove forests, to make way for engineered flood defenses such as dikes, flood walls, and drainage systems. Experts warn that this deforestation may paradoxically increase flood vulnerability, as mangroves play a crucial role in natural flood mitigation by stabilizing coastlines and absorbing storm surges. Regardless, government trajectories are still investing money to study agricultural based solution.

- **Data Gaps for the Maldives**:
  There is a lack of available data on high tide flood days for the Maldives in this dataset, limiting analysis. This absence is particularly concerning given the Maldives' extreme vulnerability to sea level rise as a low-lying island nation.

- **Trend Differences Between Countries**:
  Bangladesh shows a rising trend in minor high tide flood days over the observed period (1979–2014), consistent with rising sea levels and increased urban vulnerability. In contrast, the Philippines' flood day trends remain relatively stable, suggesting that improved infrastructure and higher coastal elevations help mitigate chronic tidal flooding, even as extreme events like typhoons remain a major threat.

Annual Precipitation Trends

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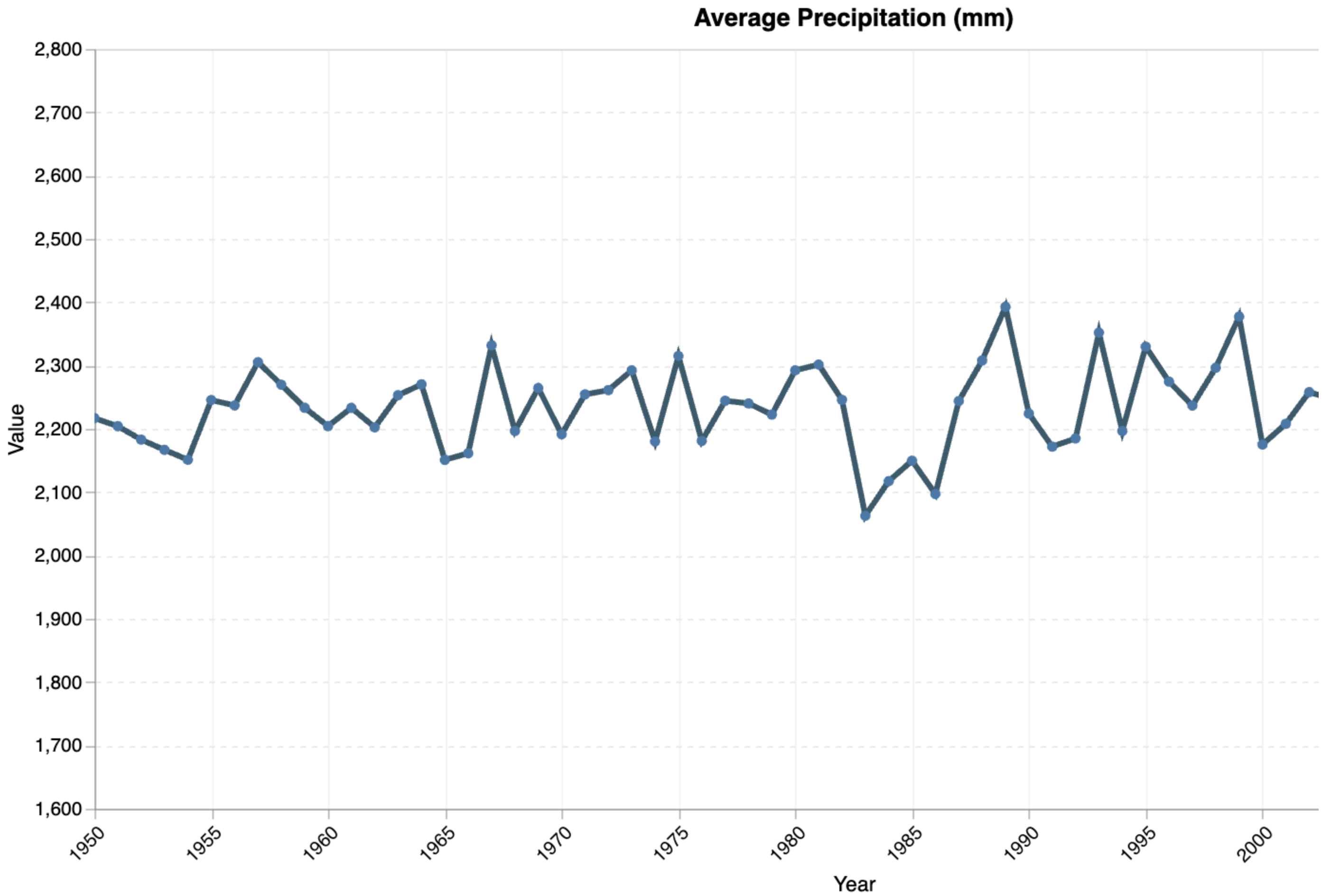

Country: Bangladesh Maldives Philippines

Observations

- **Philippines**:
  The Philippines consistently receives the **highest average annual precipitation**, around **2400–2600 mm** throughout the observed period (1950–2014).
  The trend remains relatively **stable with minor fluctuations**, suggesting that while precipitation levels vary year to year, there is **no major long-term increase or decrease** in total rainfall.

- **Maldives**:
  The Maldives experiences **lower average precipitation** compared to the Philippines, ranging roughly from **1800 mm to 2000 mm** annually.
  A slight **increasing trend** is observed after 1990, but overall precipitation levels remain relatively **stable** over the decades.
  Notably, precipitation dips and spikes correspond closely with **regional monsoon variations** and possibly **ENSO (El Niño/La Niña)** cycles.

- **Bangladesh**:
  Bangladesh shows **moderate average precipitation levels**, around **2200–2400 mm** annually.
  Unlike the Philippines, Bangladesh exhibits more **pronounced year-to-year variability**, especially around the 1980s and 1990s.

There is **no clear strong upward or downward trend**, but variability suggests **more irregular monsoon behavior**, which could complicate agricultural planning and flood risk management.

- While none of the countries show a dramatic long-term increase or decrease in total annual precipitation, **interannual variability** (the up-and-down swings from year to year) appears to **become slightly more pronounced** in Bangladesh and Maldives after 1990 – climate change can intensify

- **Stable overall rainfall** does **not guarantee stability in flood risk**:
  Even if total rainfall stays similar, **changing timing, intensity, and distribution** (e.g., heavier short bursts vs steady rains) can **increase flood risks**, especially when combined with sea level rise.

- **Climate resilience planning** should therefore not just focus on total precipitation amounts, but also on how rainfall is **distributed across seasons** and **the increasing intensity of extreme rainfall events**.

Also, although the Philippines receives more average annual precipitation, Bangladesh remains more vulnerable to persistent and chronic flooding due to its low elevation, flat geography, and slower drainage systems. Thus, geography, drainage infrastructure, and sea level rise are often more decisive factors for flood risk than total rainfall alone.

Growth Rate Trends in Key Socioeconomic Indicators

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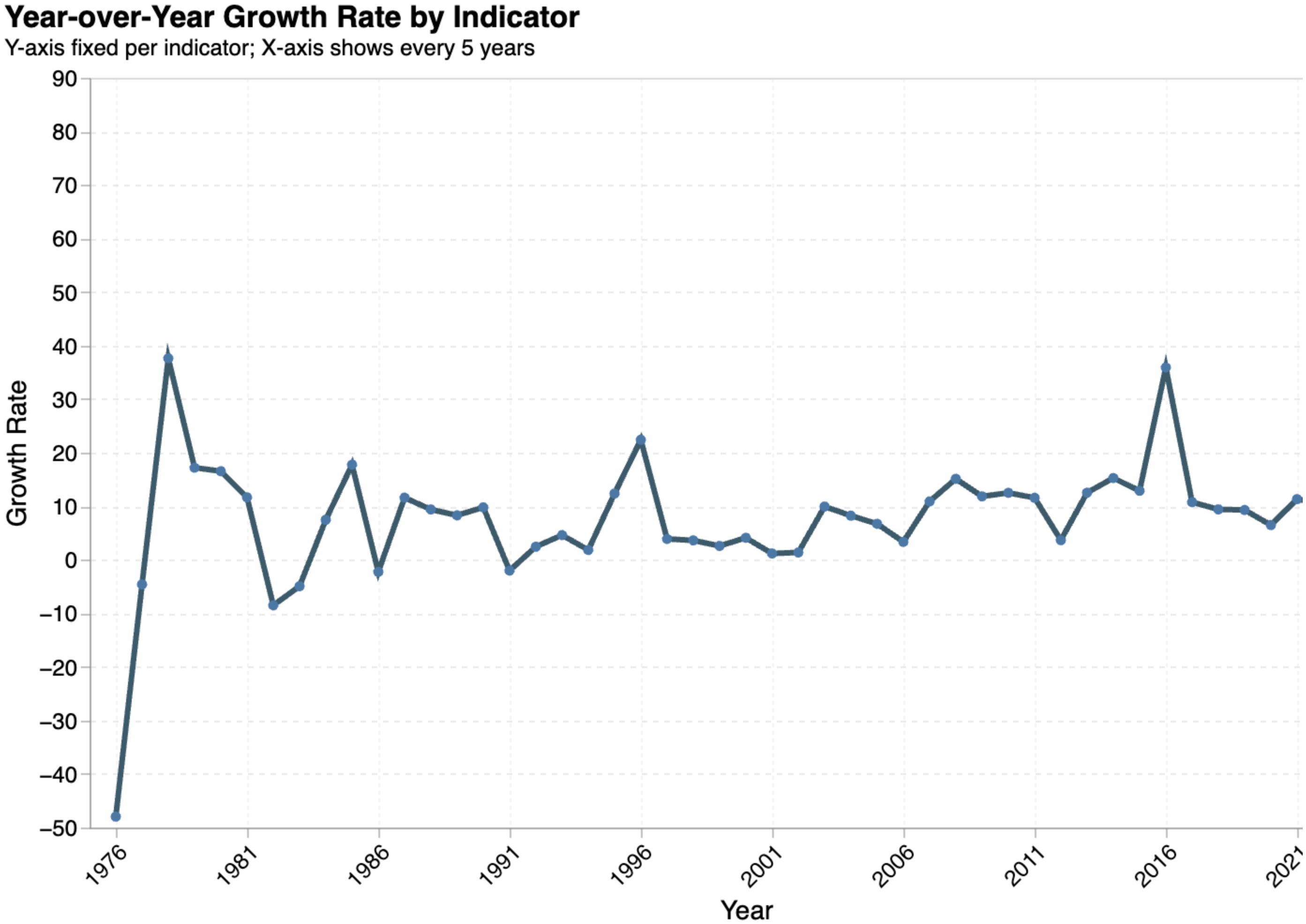

Indicator: GDP (current US$) Net migration Population, total Urban population growth (annual %)
Country: Bangladesh Maldives Philippines

Observations * Typhoon Pedring (International name: Nesat) in September 2011, which caused severe flooding, damage to infrastructure, and displacement of communities. Filipinoes were displaced and responded by climate inducd migration.

- In the early 2000s, the Maldives was still heavily dependent on tourism and fishing. Economic challenges, such as rising costs, declining fish stocks, or a downturn in global tourism, might have pushed people to seek work abroad.The Maldives is extremely vulnerable to sea level rise, and by 2000, there were increasing concerns about climate change impacts — particularly flooding and damage to homes and livelihoods. Emigration could have been driven by a sense of uncertainty about the future of island life in the face of these growing environmental challenges.

5. Climate-Society Linkages

5.1 Static Correlation Analysis: Sea Level and Socioeconomic Indicators

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```
                   Indicator  Correlation
0              Population, total    -0.436481
1              GDP (current US$)     0.049359
2  Urban population growth (annual %)     0.080229
3                  Net migration     0.321243
```

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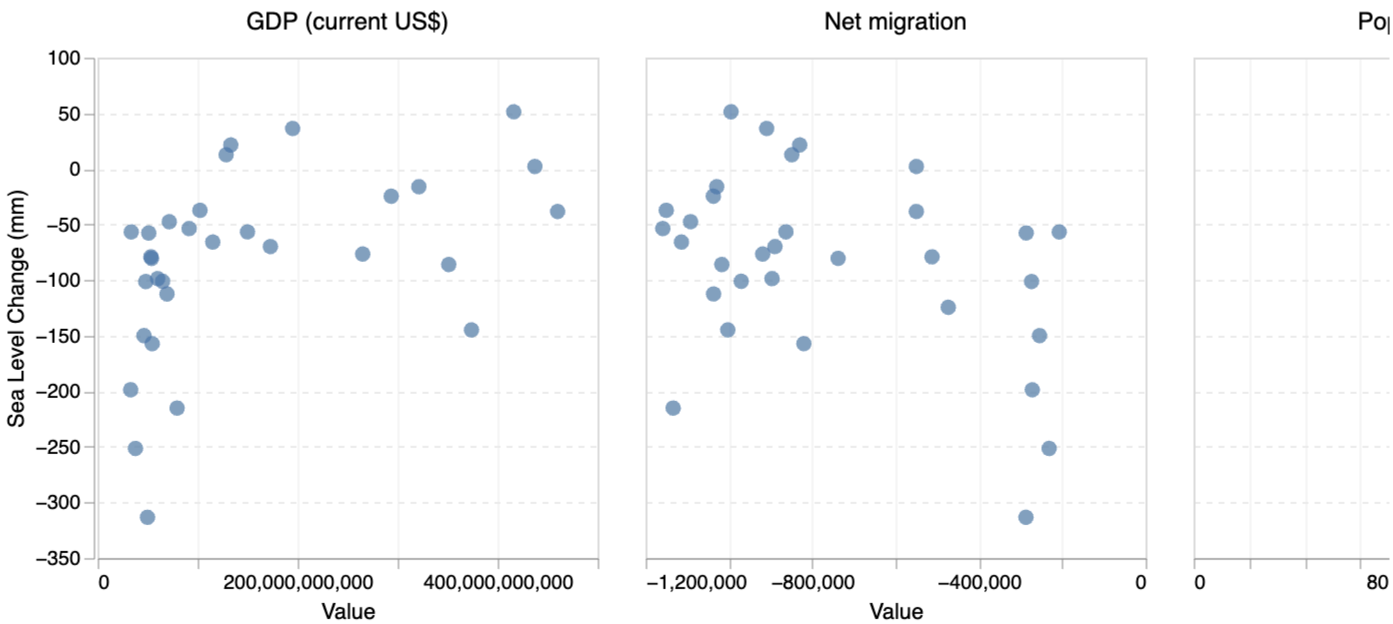

Country: ◉Bangladesh ○Maldives ○Philippines

5.2 Static Correlation Analysis: High Tide Flooding and Socioeconomic Indicators

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	Country	FloodType	Indicator	PearsonCorr
0	Bangladesh	High Tide Flood Days Minor	Population, total	0.772470
1	Bangladesh	High Tide Flood Days Minor	GDP (current US$)	0.670853
2	Bangladesh	High Tide Flood Days Minor	Urban population growth (annual %)	-0.453464
3	Bangladesh	High Tide Flood Days Minor	Net migration	-0.792875
4	Bangladesh	High Tide Flood Days Moderate	Population, total	0.710965
5	Bangladesh	High Tide Flood Days Moderate	GDP (current US$)	0.614346
6	Bangladesh	High Tide Flood Days Moderate	Urban population growth (annual %)	-0.383359
7	Bangladesh	High Tide Flood Days Moderate	Net migration	-0.774992

	Country	FloodType	Indicator	PearsonCorr
8	Bangladesh	High Tide Flood Days Major	Population, total	0.682697
9	Bangladesh	High Tide Flood Days Major	GDP (current US$)	0.629314
10	Bangladesh	High Tide Flood Days Major	Urban population growth (annual %)	-0.312205
11	Bangladesh	High Tide Flood Days Major	Net migration	-0.730866
12	Maldives	High Tide Flood Days Minor	Population, total	NaN
13	Maldives	High Tide Flood Days Minor	GDP (current US$)	NaN
14	Maldives	High Tide Flood Days Minor	Urban population growth (annual %)	NaN
15	Maldives	High Tide Flood Days Minor	Net migration	NaN
16	Maldives	High Tide Flood Days Moderate	Population, total	NaN
17	Maldives	High Tide Flood Days Moderate	GDP (current US$)	NaN
18	Maldives	High Tide Flood Days Moderate	Urban population growth (annual %)	NaN
19	Maldives	High Tide Flood Days Moderate	Net migration	NaN
20	Maldives	High Tide Flood Days Major	Population, total	NaN
21	Maldives	High Tide Flood Days Major	GDP (current US$)	NaN
22	Maldives	High Tide Flood Days Major	Urban population growth (annual %)	NaN
23	Maldives	High Tide Flood Days Major	Net migration	NaN
24	Philippines	High Tide Flood Days Minor	Population, total	0.485540
25	Philippines	High Tide Flood Days Minor	GDP (current US$)	0.308777
26	Philippines	High Tide Flood Days Minor	Urban population growth (annual %)	-0.237078
27	Philippines	High Tide Flood Days Minor	Net migration	-0.187197
28	Philippines	High Tide Flood Days Moderate	Population, total	0.461451
29	Philippines	High Tide Flood Days Moderate	GDP (current US$)	0.282281
30	Philippines	High Tide Flood Days Moderate	Urban population growth (annual %)	-0.237274
31	Philippines	High Tide Flood Days Moderate	Net migration	-0.207153
32	Philippines	High Tide Flood Days Major	Population, total	0.401449
33	Philippines	High Tide Flood Days Major	GDP (current US$)	0.217387
34	Philippines	High Tide Flood Days Major	Urban population growth (annual %)	-0.313352
35	Philippines	High Tide Flood Days Major	Net migration	-0.361113

5.3 Rolling Correlation Analysis Over Time

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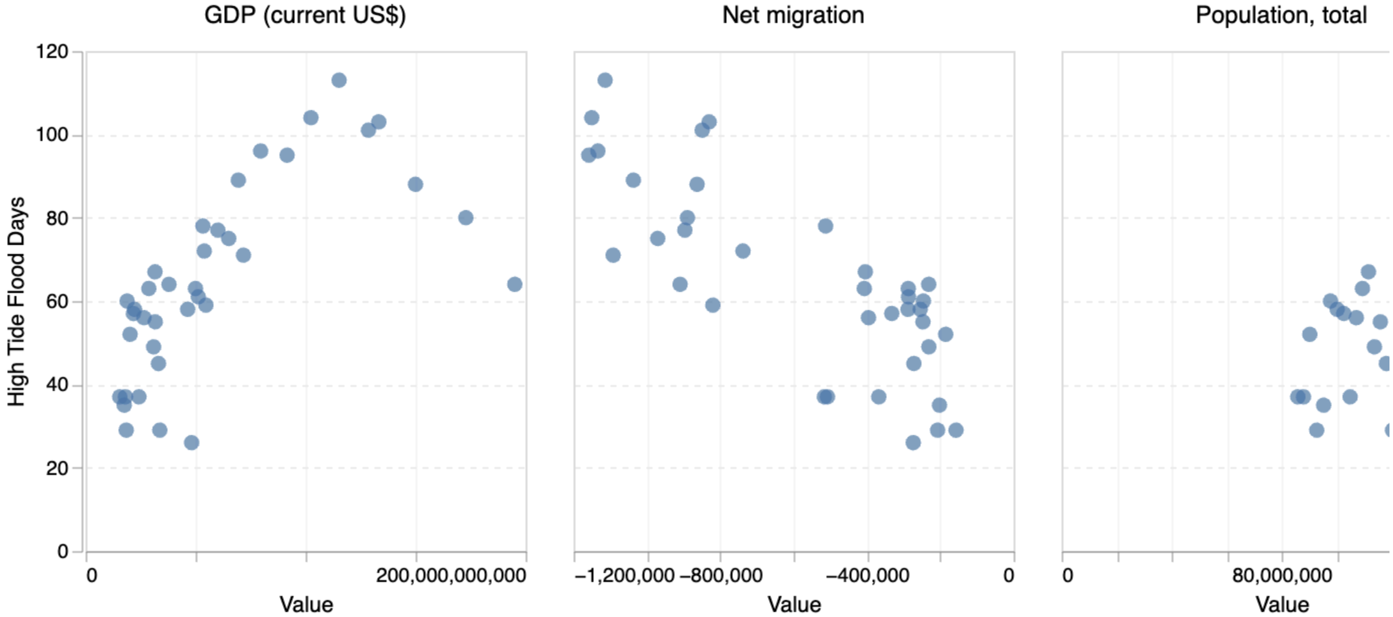

Flood Type: High Tide Flood Days Minor High Tide Flood Days Moderate High Tide Flood Days Majo

Country: Bangladesh Maldives Philippines

Temporal Dynamics: Rolling and Lead-Lag Correlations

We compute 10-year rolling correlations between climate stressors and urbanization or migration indicators.

Lead-lag analysis allows us to detect which factors tend to precede changes in others — helping explore possible causal pathways.

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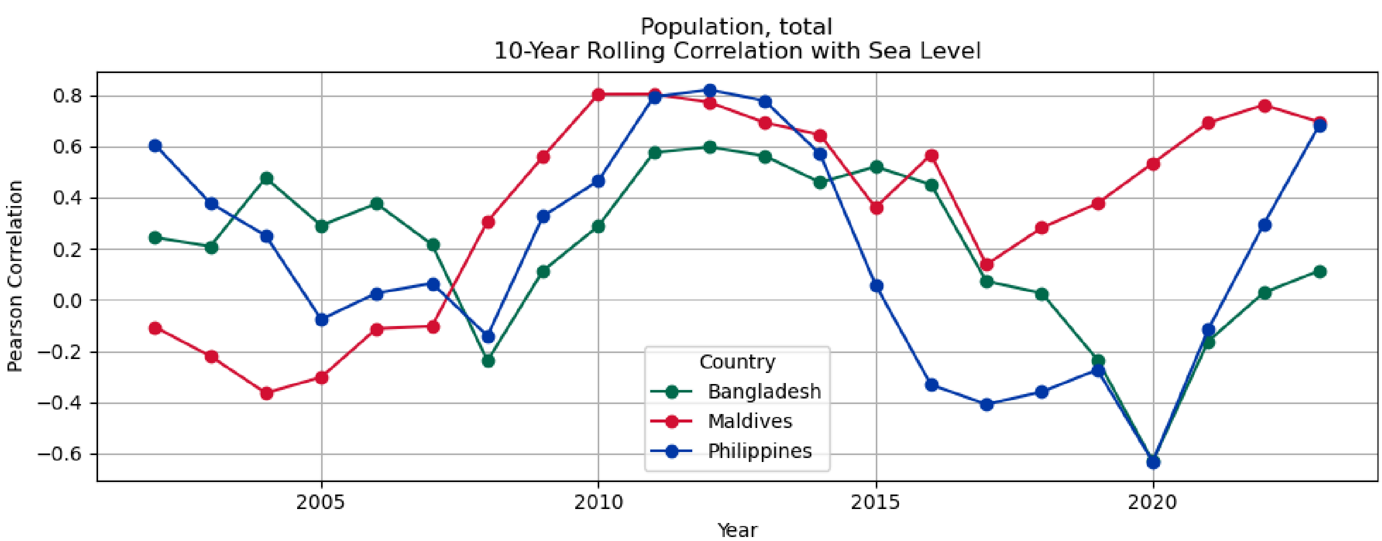

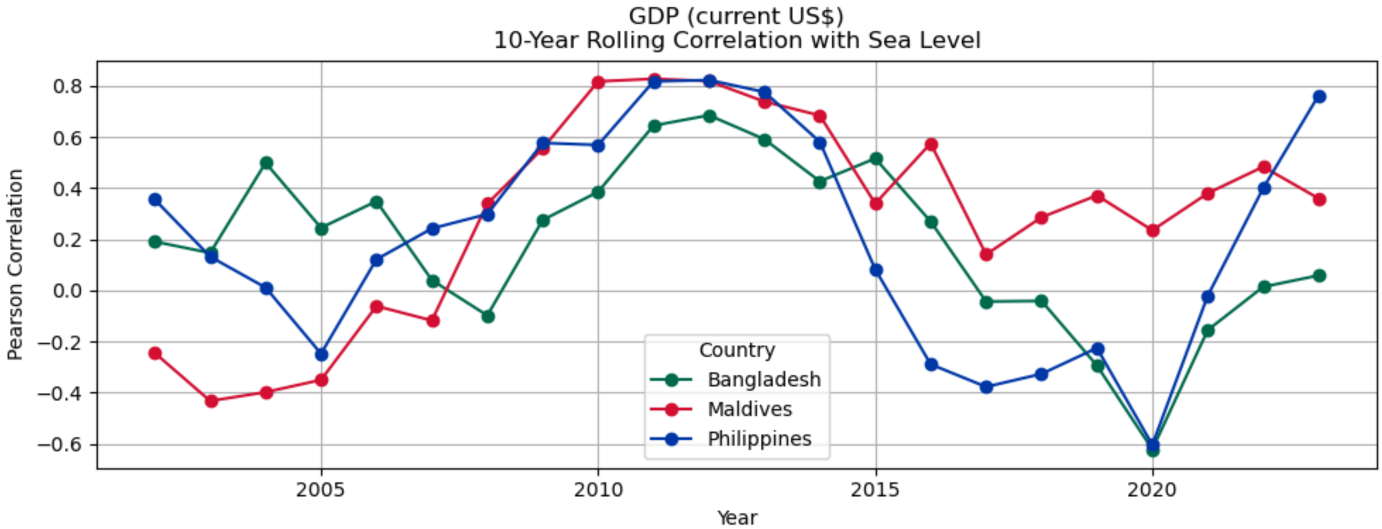

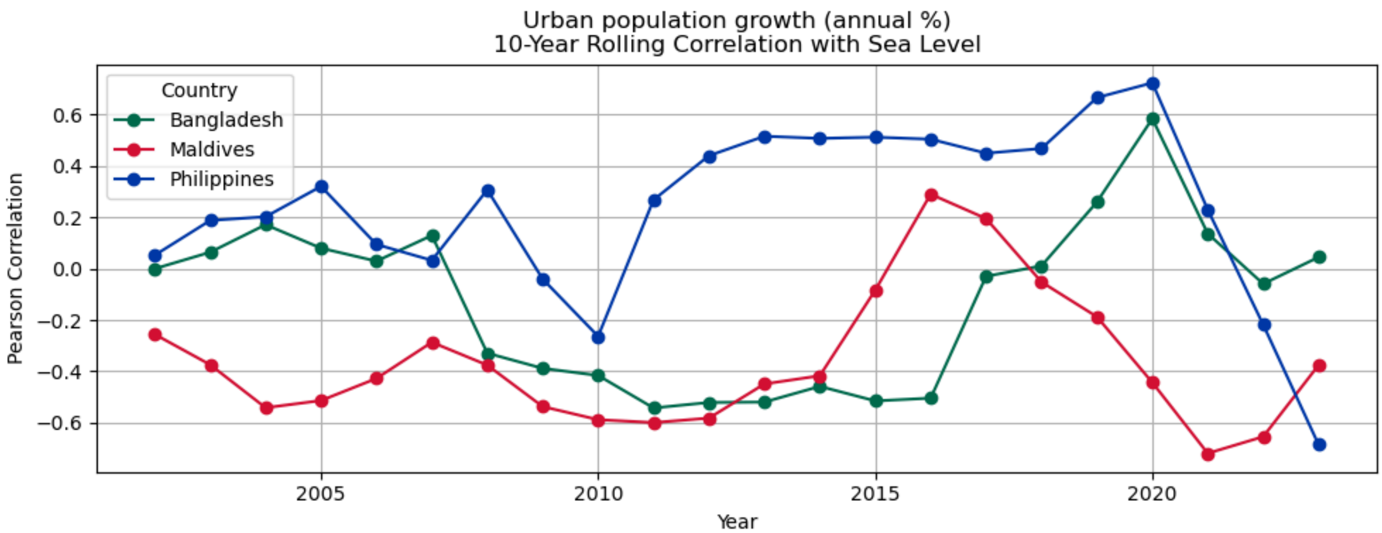

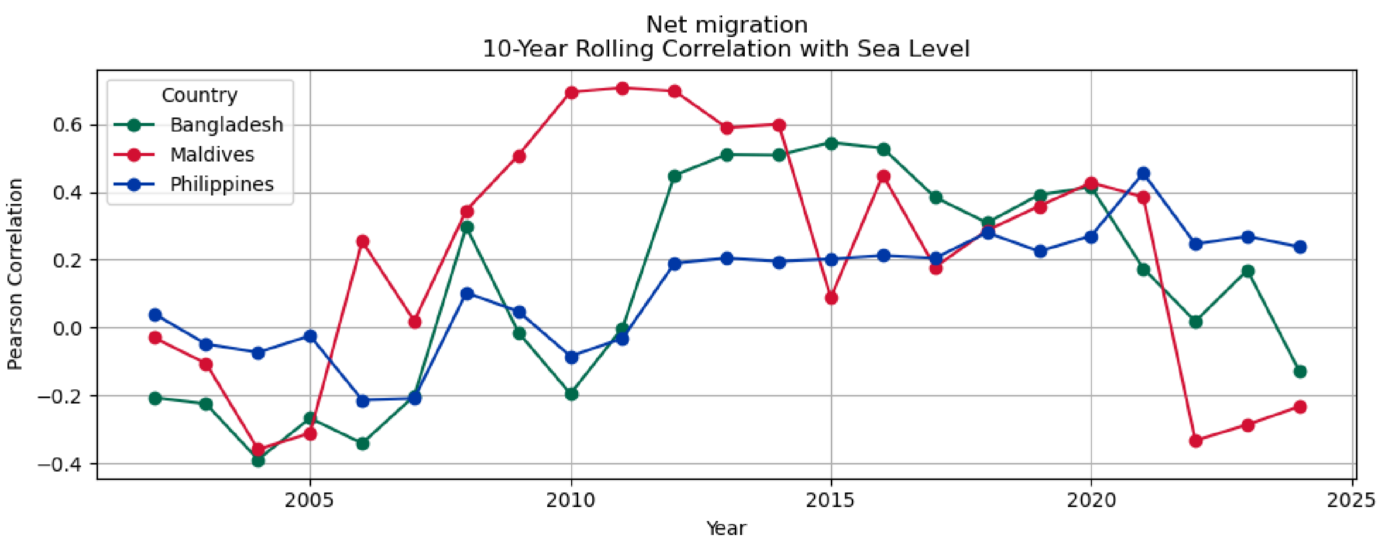

- Population, total
  - Maldives: Consistently high positive correlation (≈0.8–0.95), indicating that population size and sea level rise in near lockstep.

  - Bangladesh & Philippines: Exhibit greater cyclical fluctuations—some decades show high correlation (≈0.7–0.9), while others drop to near zero or even negative values, reflecting the influence of coastal migration, urbanization, and major climate events on synchronization.
- GDP (current US$)
  - Maldives: Maintains a strong positive correlation, suggesting long-term alignment between economic growth and sea level rise.
  - Bangladesh & Philippines: Correlation fluctuates across decades—peaking at 0.6–0.8 in some periods but weakening significantly in others, likely due to economic crises, reforms, or industrial shifts.
- Urban population growth (annual %)
  - Bangladesh & Philippines: Correlation rises (e.g., 0.6–0.8 during rapid urbanization decades like the 2000s), indicating tighter coupling between urban expansion and sea level rise.
  - Maldives: Minimal fluctuations in urbanization rates sustain high correlation (>0.7), as both population and urban growth remain closely tied to sea level changes.
- Net migration
  - All three countries display noisier correlations:
  - Some decades show positive correlation (increased migration driven by sea level rise).
  - Others show negative correlation (higher migration rates despite stable sea levels), reflecting the complex interplay of economic, policy, and environmental drivers.

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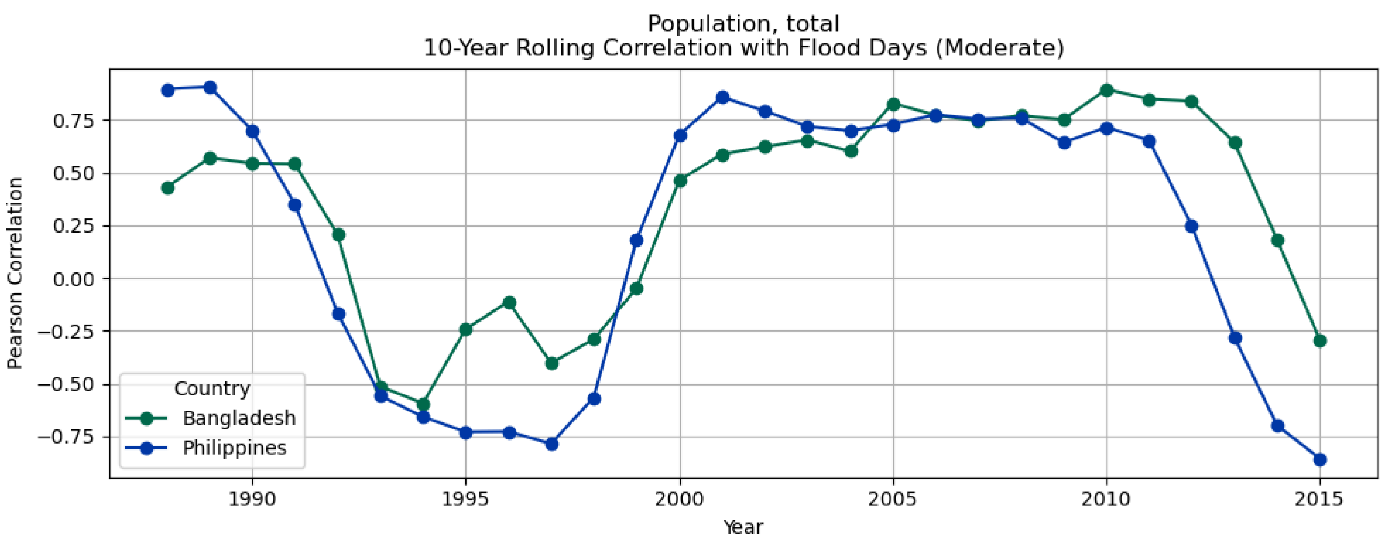
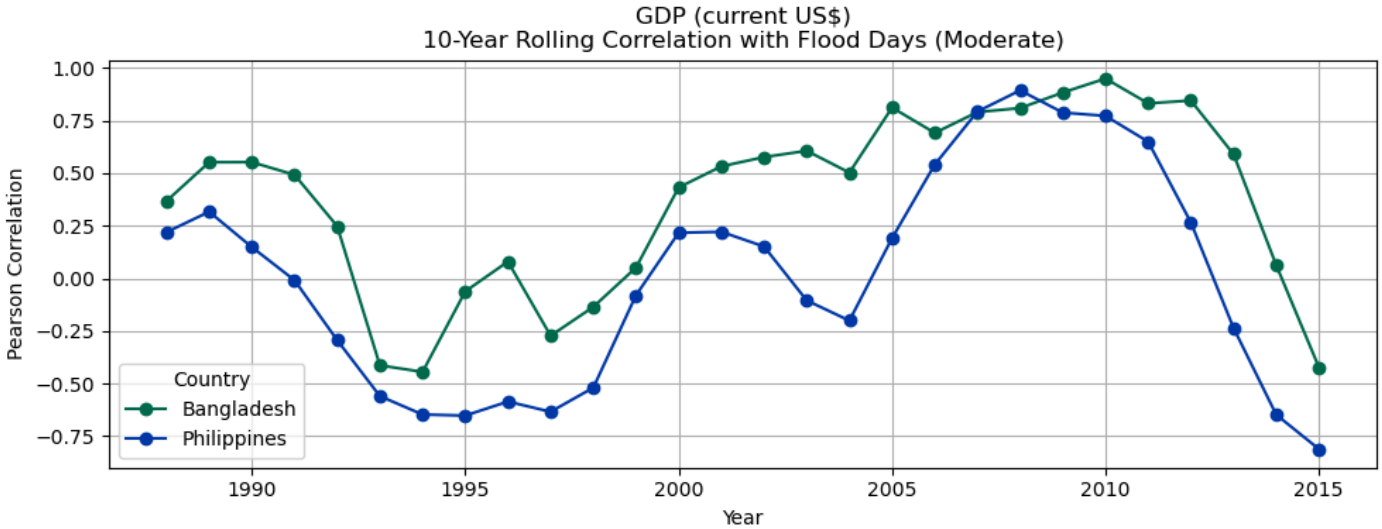
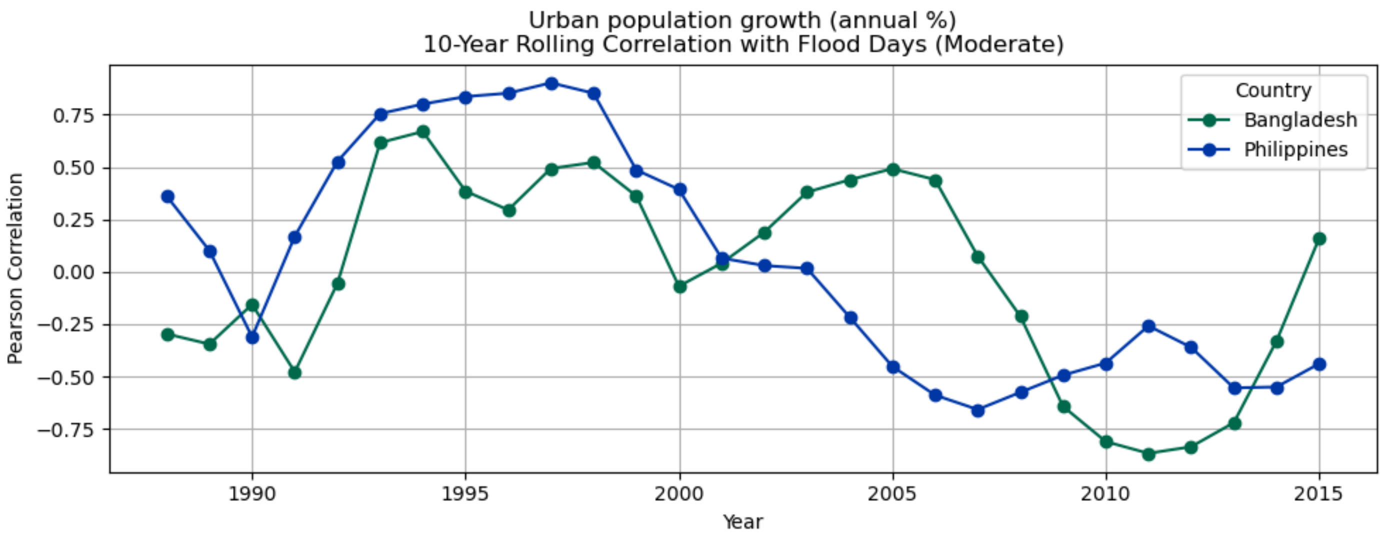
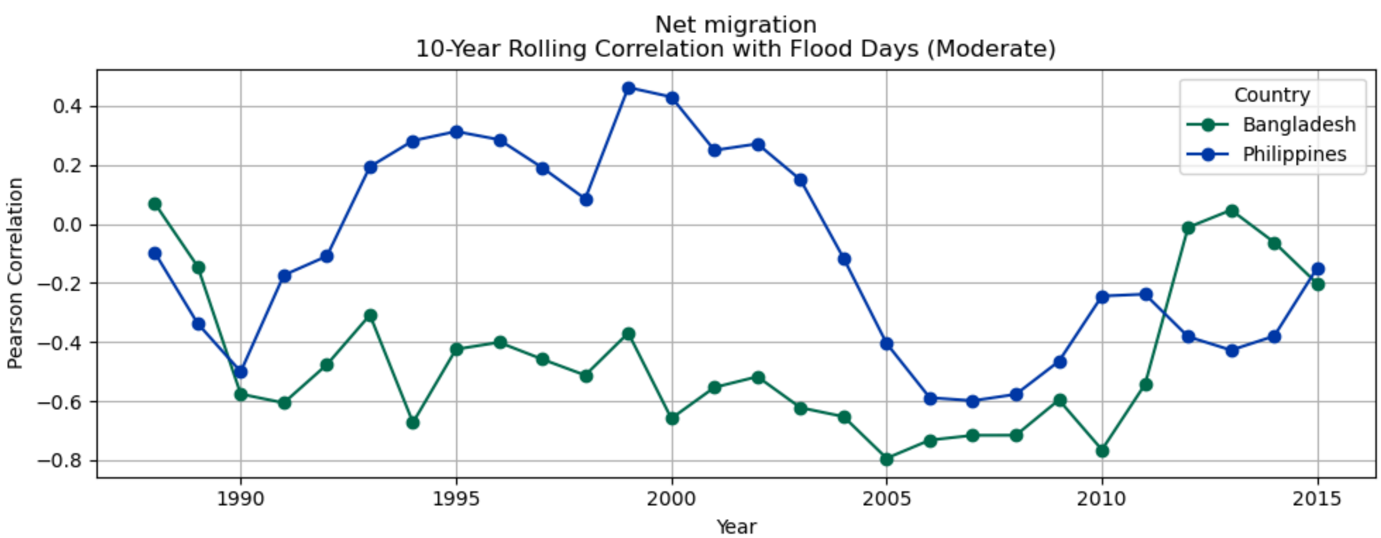



GDP (current US$)
10-Year Rolling Correlation with Flood Days (Moderate)
Pearson Correlation
Year
Country
Bangladesh
Philippines
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
1990
1995
2000
2005
2010
2015


Urban population growth (annual %)
10-Year Rolling Correlation with Flood Days (Moderate)
Pearson Correlation
Year
Country
Bangladesh
Philippines
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
1990
1995
2000
2005
2010
2015


Net migration
10-Year Rolling Correlation with Flood Days (Moderate)
Pearson Correlation
Year
Country
Bangladesh
Philippines
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
1990
1995
2000
2005
2010
2015

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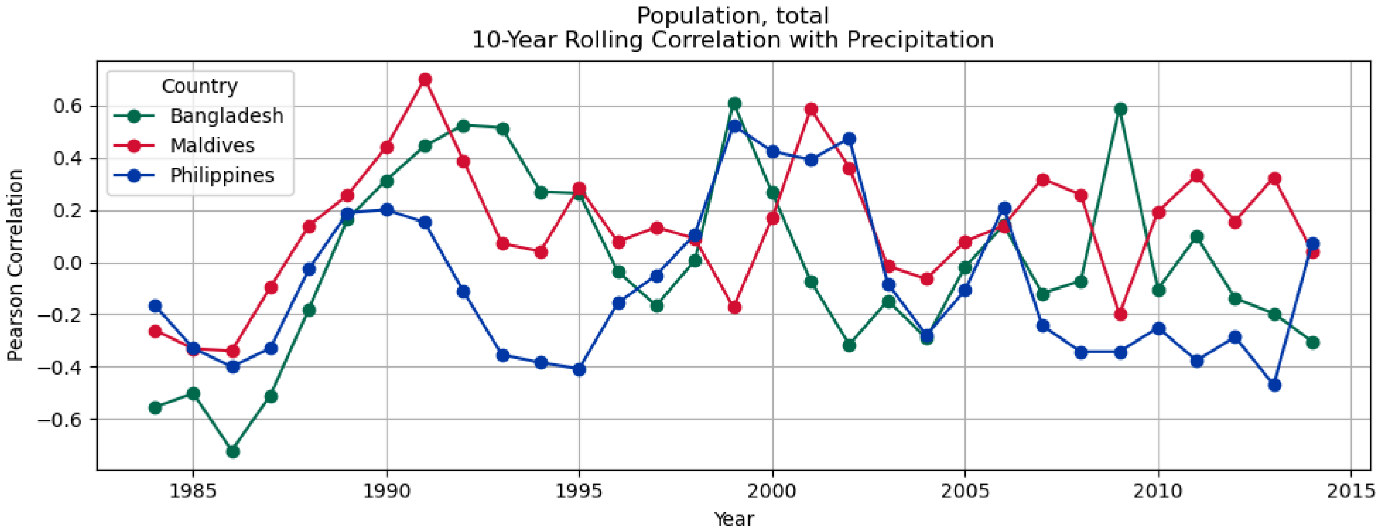
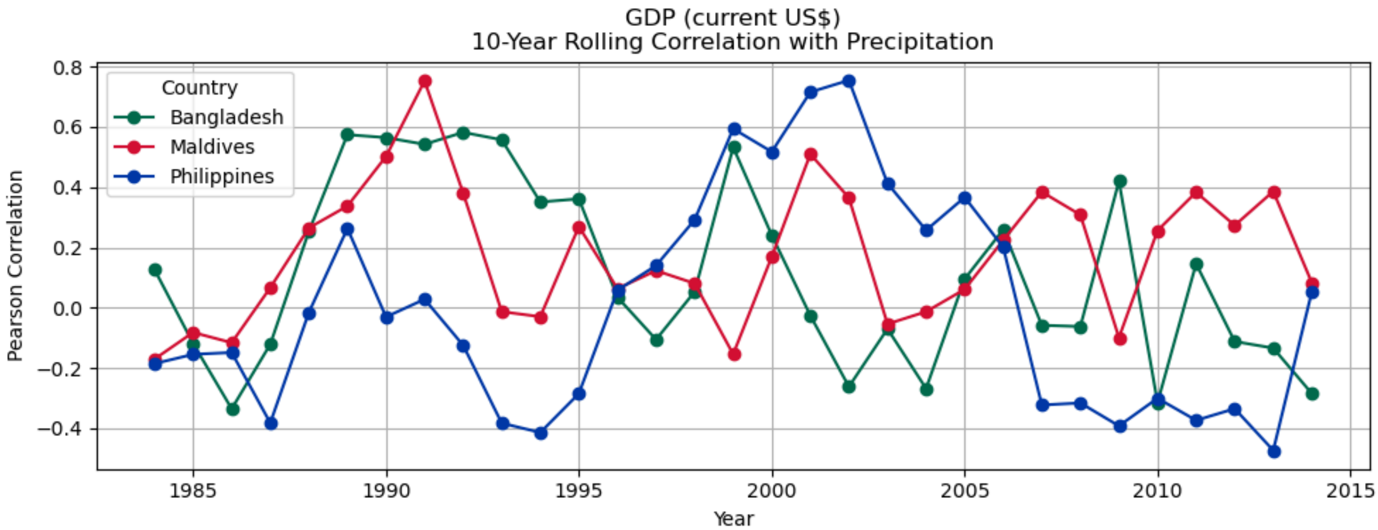
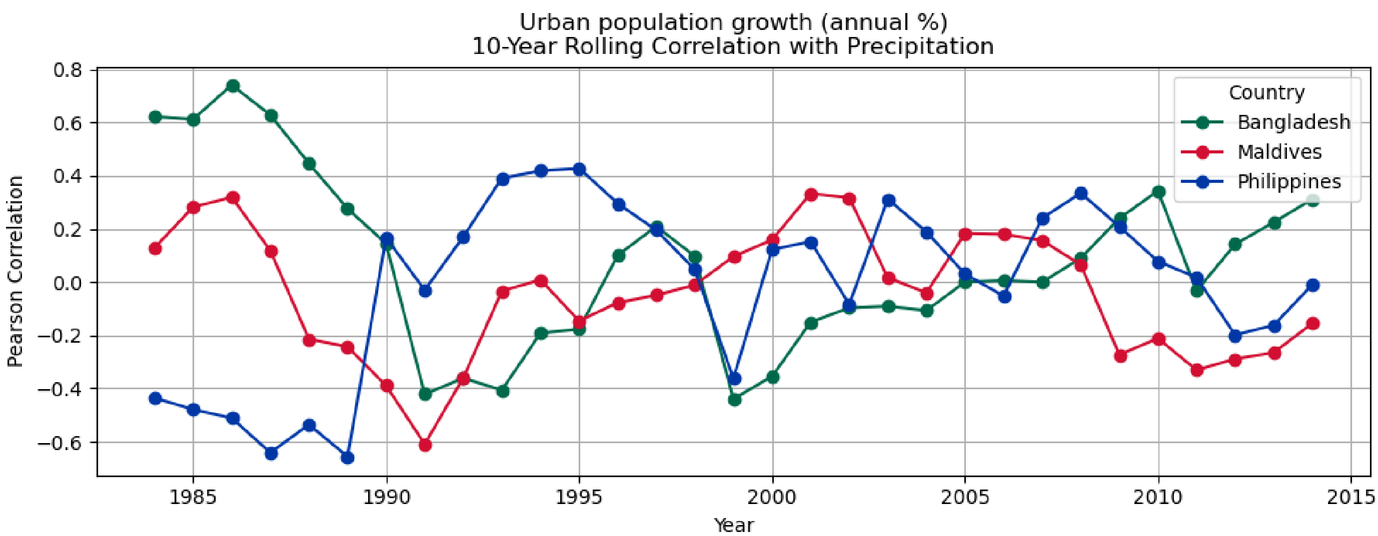
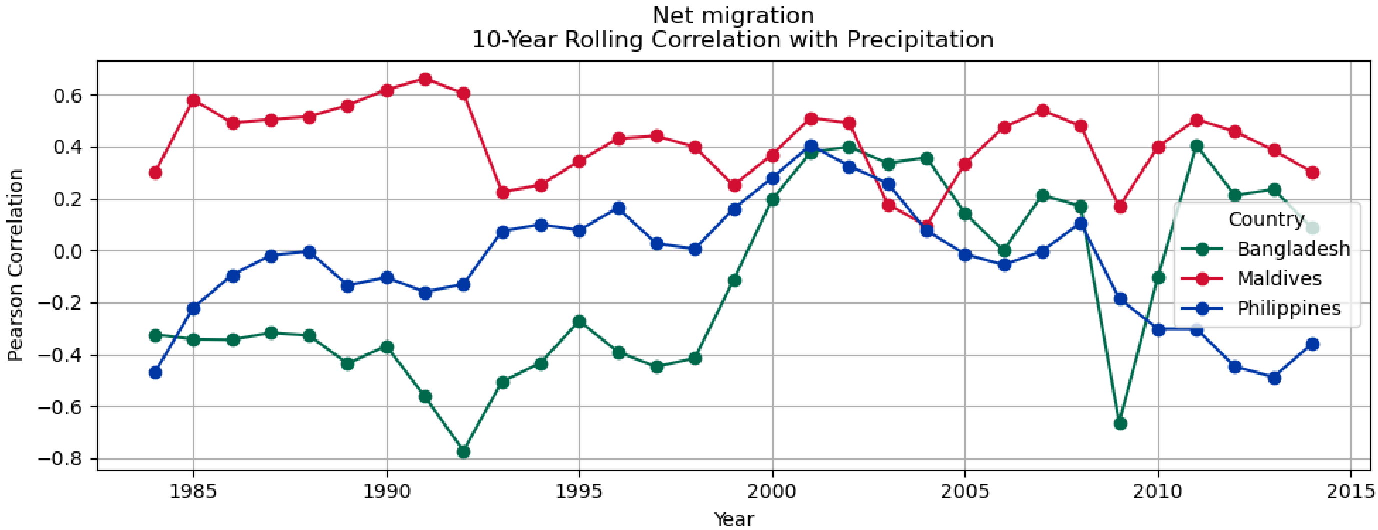
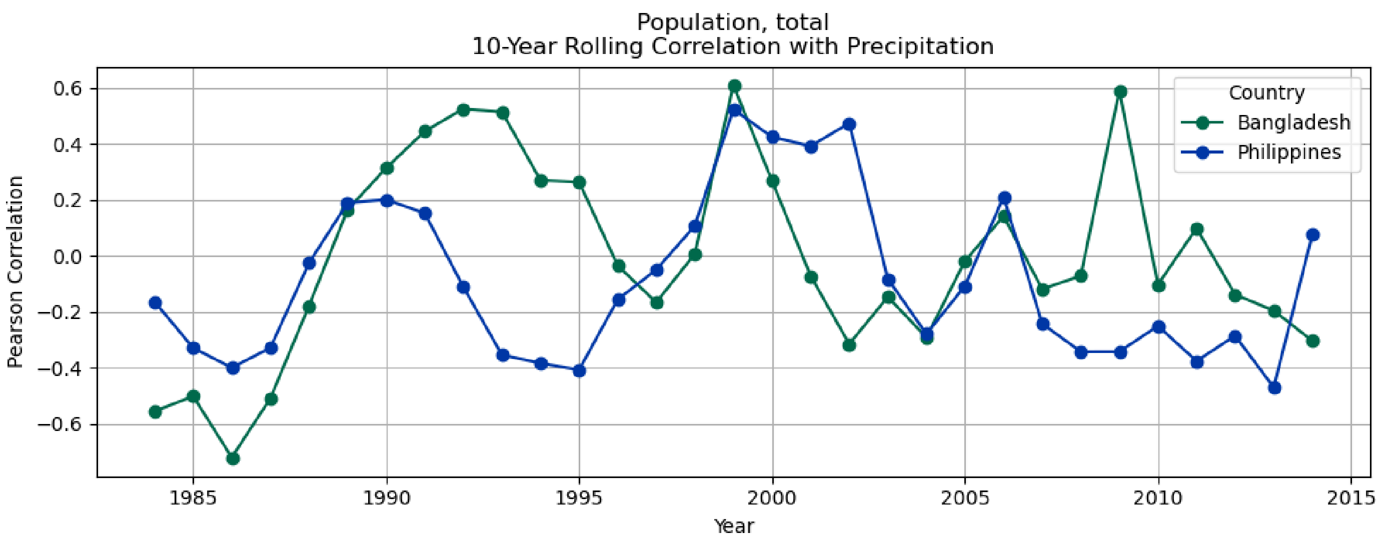

Population, total
10-Year Rolling Correlation with Precipitation
Country
Bangladesh
Maldives
Philippines
Pearson Correlation
Year

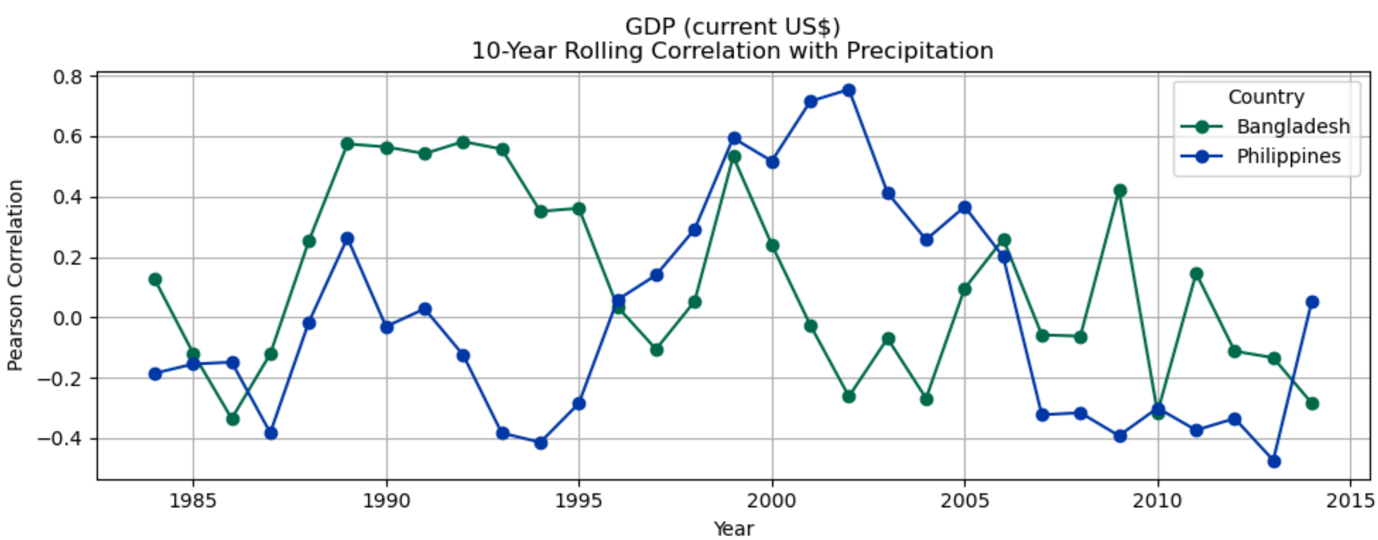

GDP (current US$)
10-Year Rolling Correlation with Precipitation
Country
Bangladesh
Maldives
Philippines
Pearson Correlation
Year

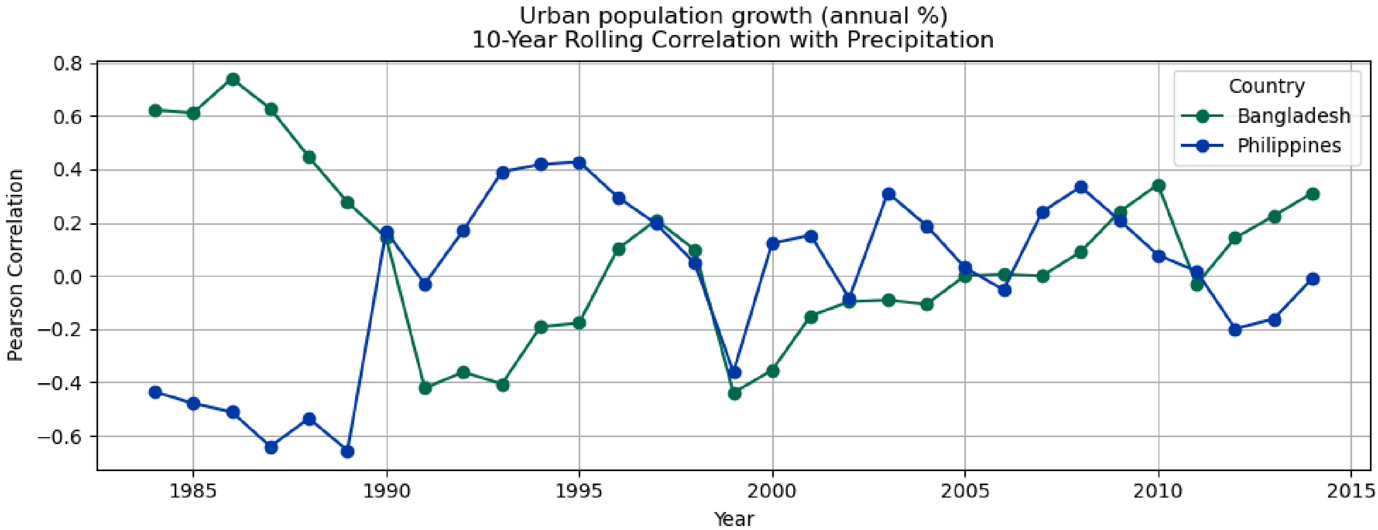

Urban population growth (annual %)
10-Year Rolling Correlation with Precipitation
Country
Bangladesh
Maldives
Philippines
Pearson Correlation
Year

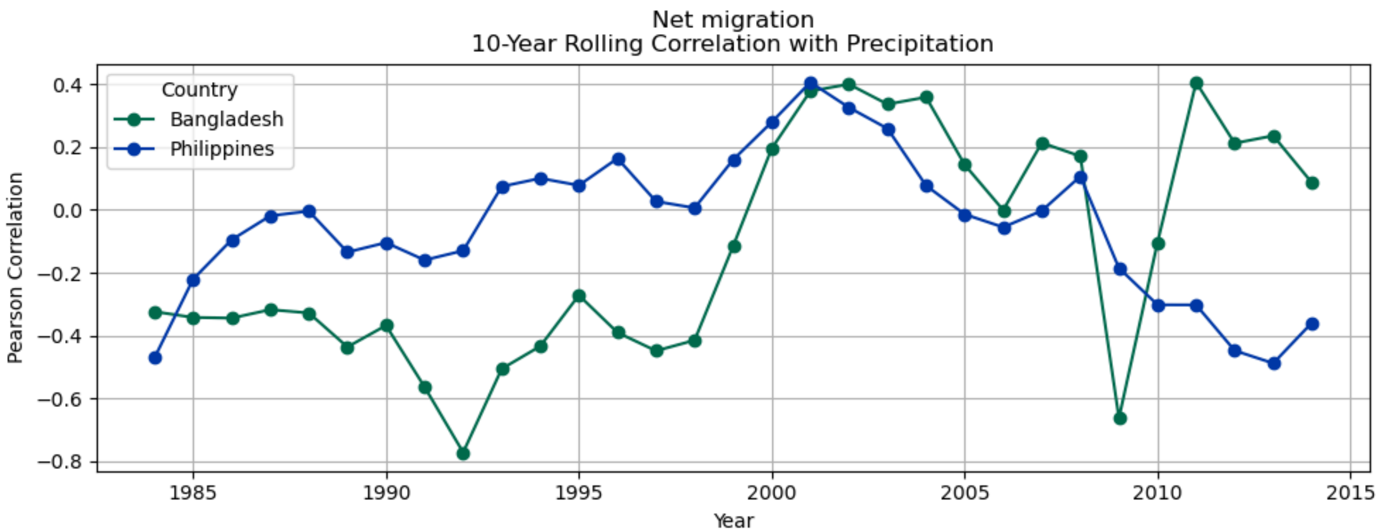

Net migration
10-Year Rolling Correlation with Precipitation
Pearson Correlation
Year
Country
Bangladesh
Maldives
Philippines

▶ Show Code


Population, total
10-Year Rolling Correlation with Precipitation
Pearson Correlation
Year
Country
Bangladesh
Philippines


GDP (current US$)
10-Year Rolling Correlation with Precipitation
Pearson Correlation
Year
Country
Bangladesh
Philippines





5.4 Lead-Lag Cross Correlation Analysis

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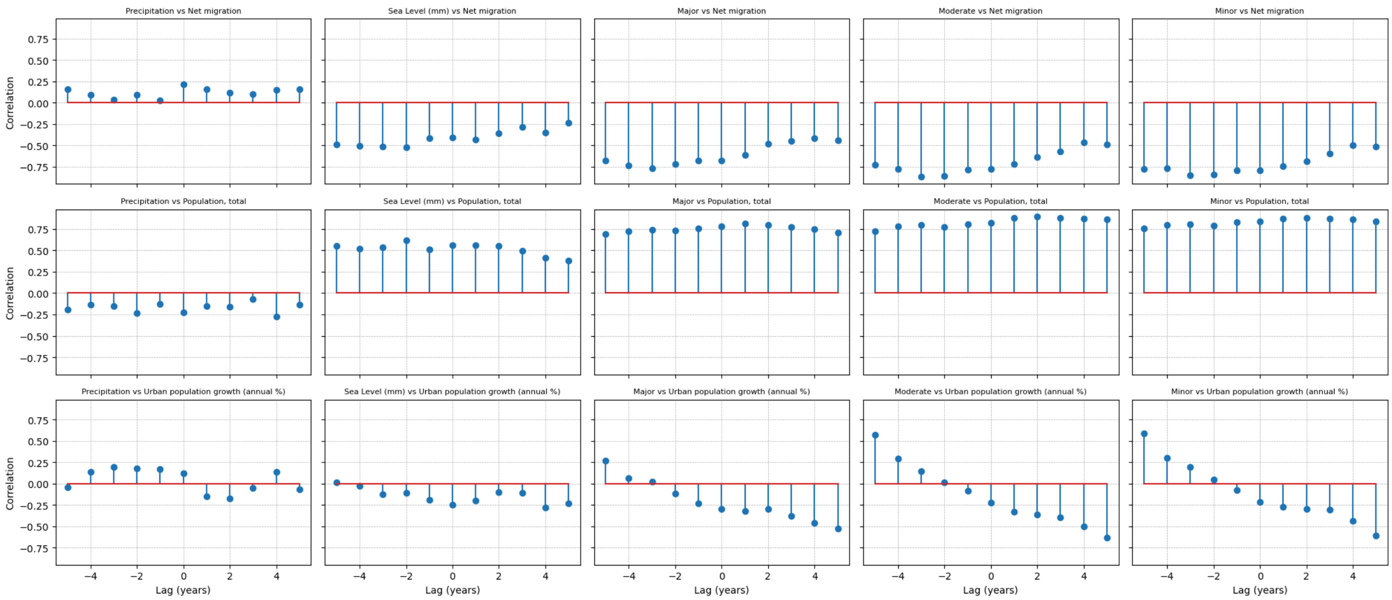
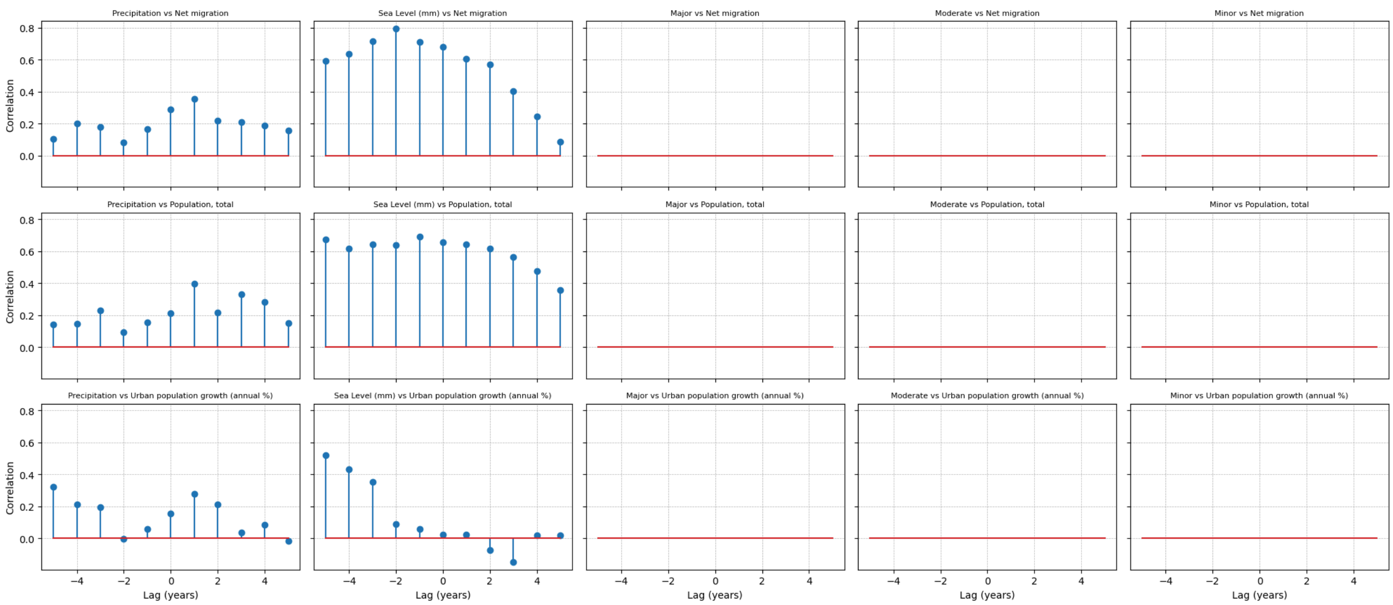
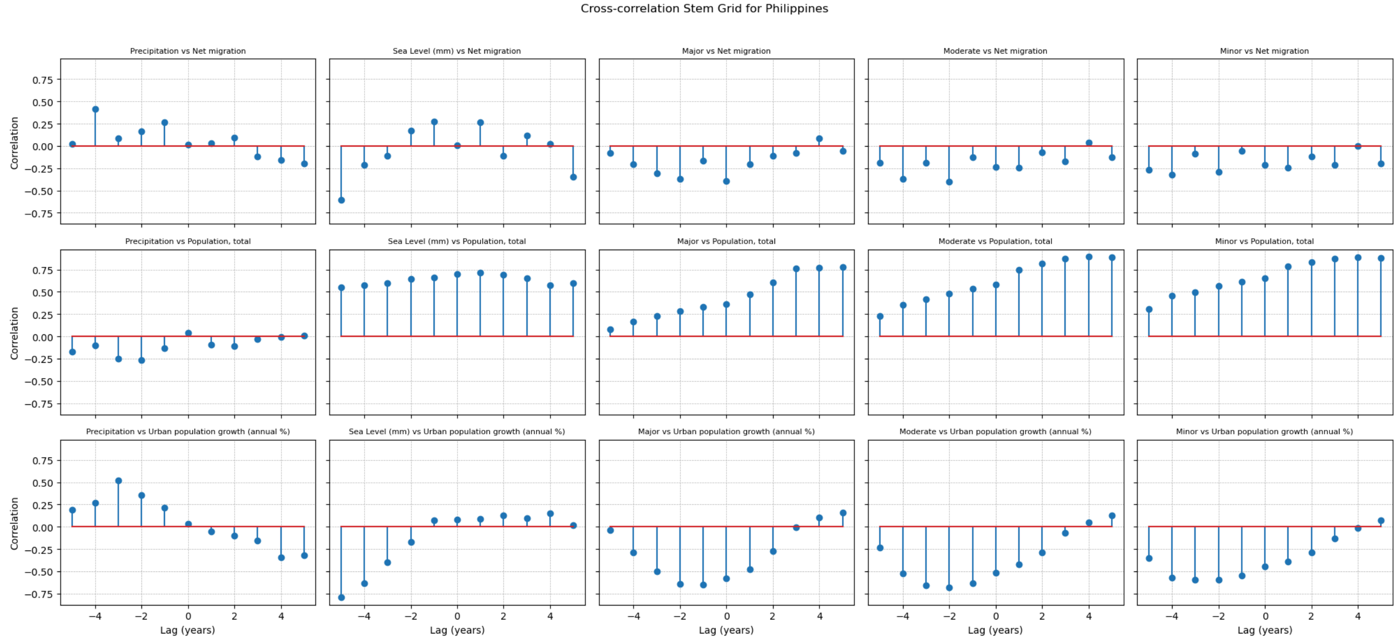
Cross-correlation Stem Grid for Bangladesh



Cross-correlation Stem Grid for Maldives





- Peak at lag = 0 A high stem at 0 means the two series co-vary in the same year.
- Peak at positive lag Suggests that fluctuations in the climate variable tend to be followed by changes in the social indicator after that many years. E.g. a big positive spike at lag = +1 for (Major flood days) → (Net migration) would imply that heavy flooding in year t tends to push migration up in year _t + 1.
- Peak at negative lag Less intuitive for climate→social, but could point to pre-conditioning or data quirks—e.g. a social trend that reliably precedes a measured climate anomaly (or artifacts of smoothing, indexing, etc.).

By scanning across the grid, you can see which climate stressors have the strongest contemporaneous (lag = 0) or delayed (lag > 0) impacts on each social outcome, and compare relative timings (flood days vs. sea-level vs. precipitation). these plots help you identify not just whether a climate stressor correlates with a social outcome, but also when that effect is strongest—offering clues about the temporal dynamics of climate-driven social change.

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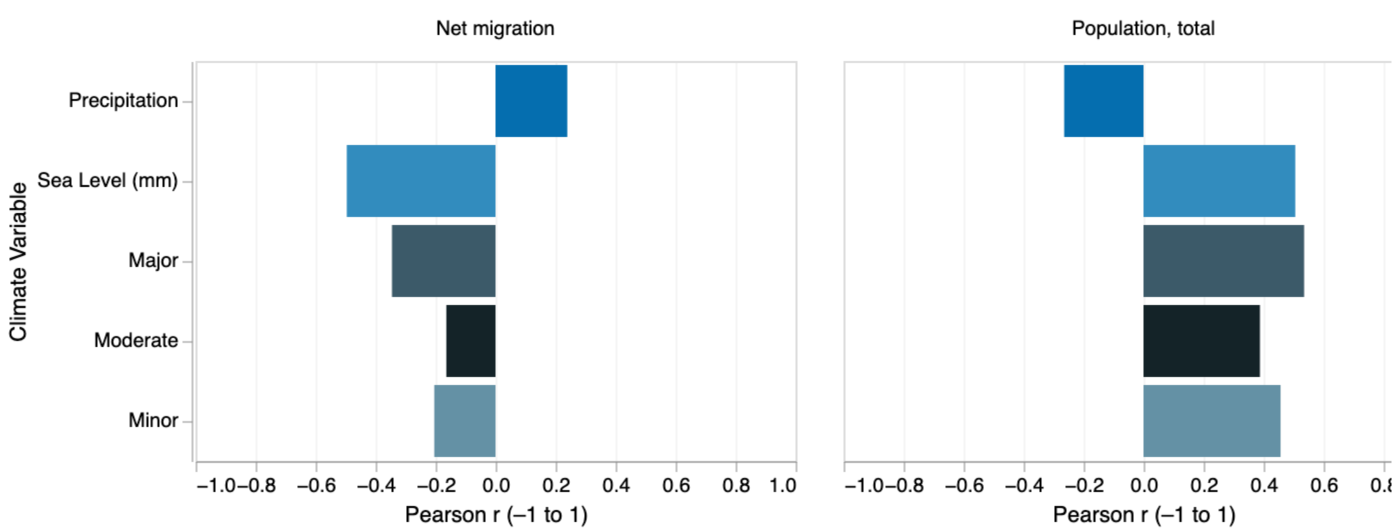

Country: Bangladesh

Lag (years): -10

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	Country	Lag	Social	Feature	Correlation
0	Bangladesh	-3	Net migration	Moderate	-0.862465
1	Bangladesh	2	Population, total	Moderate	0.893918
2	Bangladesh	-7	Urban population growth (annual %)	Major	0.859850
3	Maldives	-9	Net migration	Sea Level (mm)	0.841584
4	Maldives	-8	Population, total	Sea Level (mm)	0.809769
5	Maldives	-8	Urban population growth (annual %)	Sea Level (mm)	0.874793
6	Philippines	-10	Net migration	Minor	0.796351
7	Philippines	6	Population, total	Moderate	0.908019
8	Philippines	-5	Urban population growth (annual %)	Sea Level (mm)	-0.790678

6. Vulnerability Assessment

To summarize exposure, we create a **Composite Vulnerability Index** for each country-year.

Steps: - Normalize indicators (e.g., GDP, sea level, flood counts) to a 0–1 scale. - Average normalized indicators to compute the index.

This index captures multi-dimensional vulnerability in a single, comparable score.

6.1 Composite Vulnerability Index

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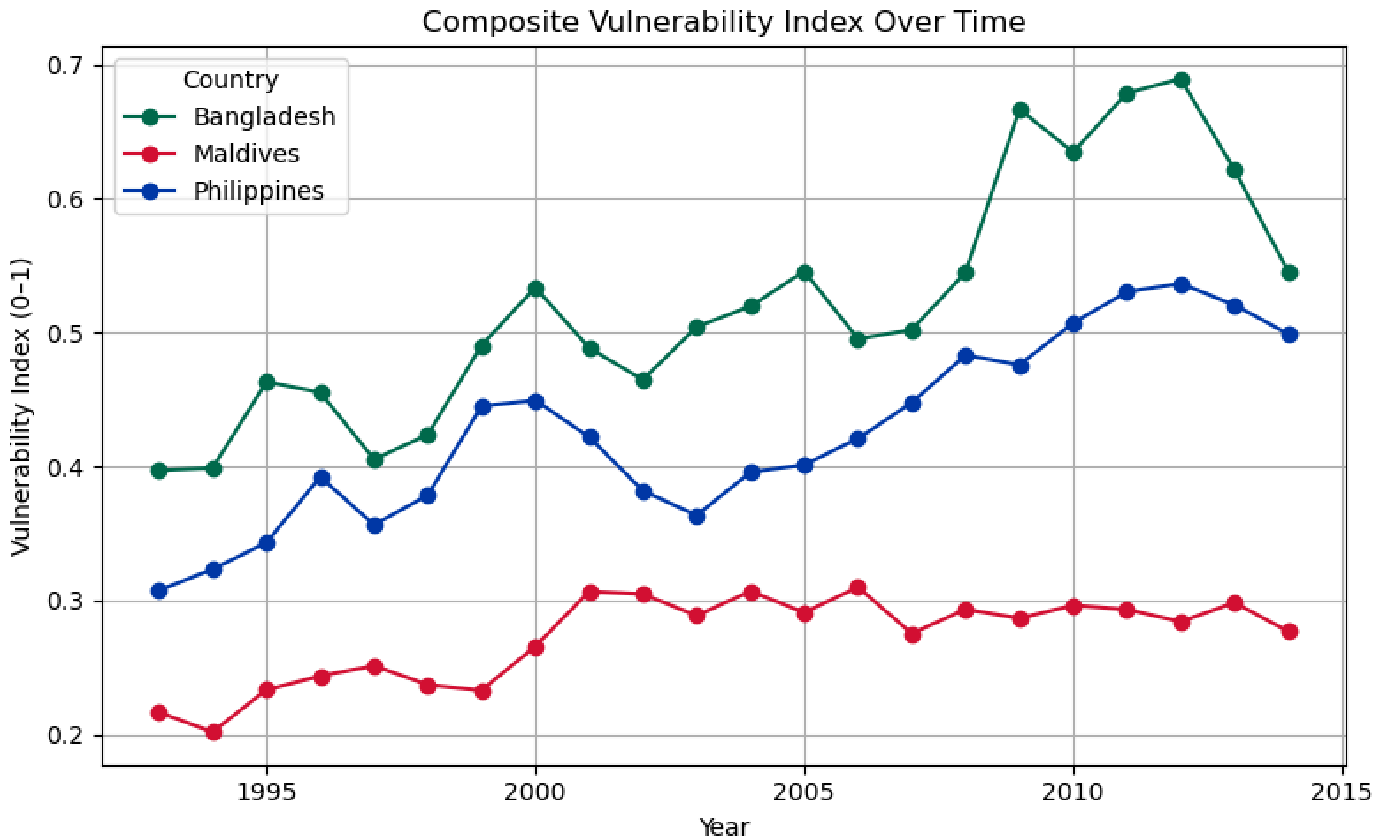

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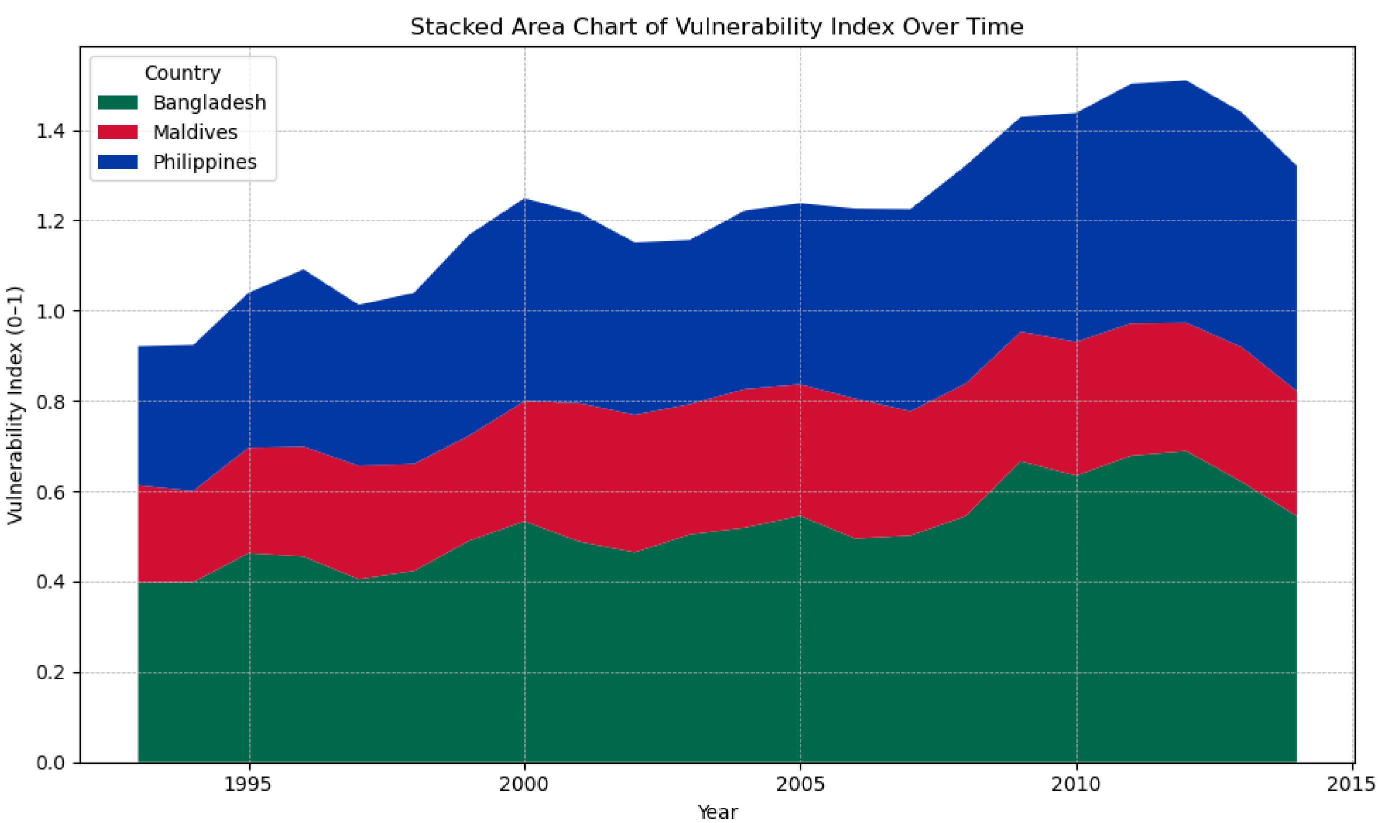

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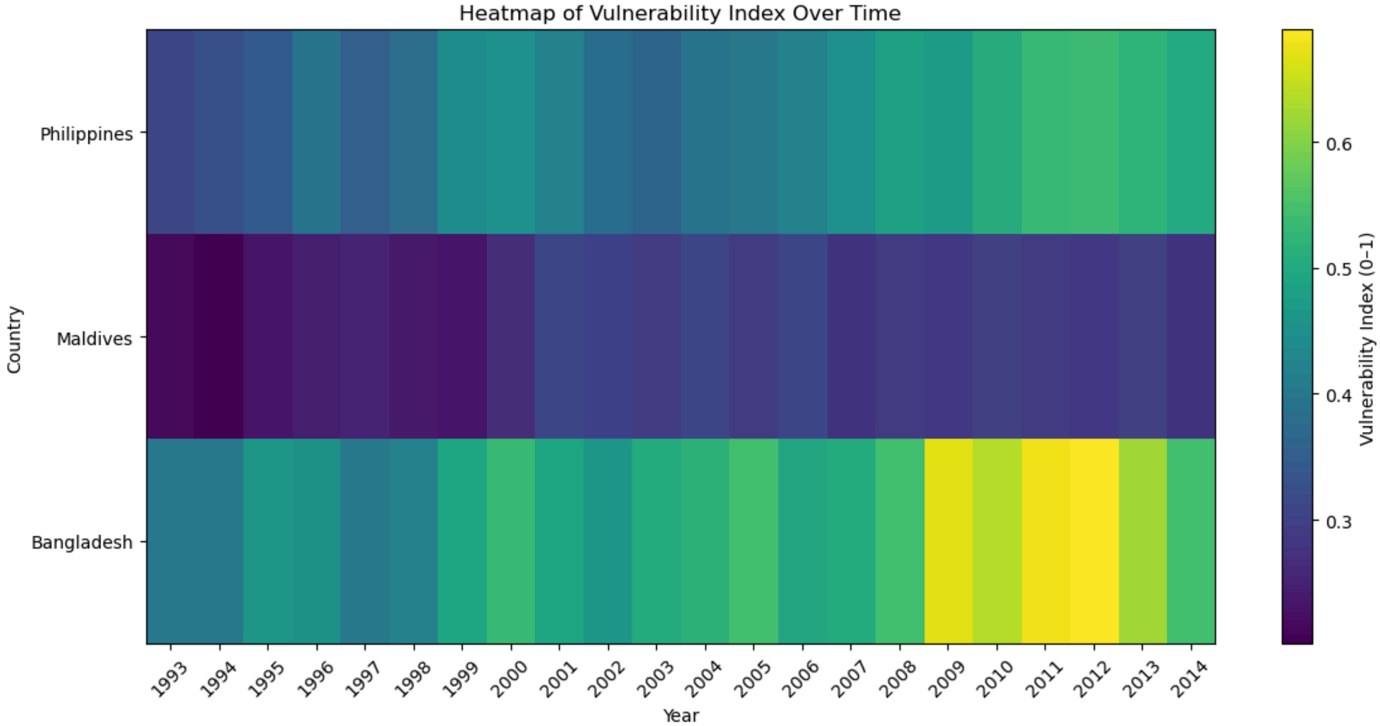

7. Comparative Analysis

We will summarize our findings with a comparison of the three cities to assess: - Common traits (e.g., sea level rise exposure) - Unique challenges (e.g., land subsidence, migration pressure) - Differences in climate resilience and adaptation needs.

8. Conclusion and Policy Implications