Assessment of Precipitation Trends in Major Latin American and European Metropolitan Regions: Implications for Urban Water Management

Évaluation des tendances des précipitations dans les principales régions métropolitaines d'Amérique latine et d'Europe : implications pour la gestion des eaux urbaines

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RÉSUMÉ

Les systèmes de drainage urbains, conçus sous l'hypothèse de la stationnarité climatique, sont confrontés à des défis croissants en raison de l'évolution des régimes de précipitations. Cette étude évalue les tendances de cinq indices cruciaux pour la conception et l'operation des infrastructures urbaines pour la gestion de l'eau: les précipitations maximales sur 1 et 3 jours, le nombre de jours secs, les précipitations annuelles totales et la variabilité de la saison de pluie – en utilisant les données provenant de 24 585 postes pluviométriques en Amérique latine et en Europe (1900–2024). Les résultats mettent en évidence des configurations régionales distinctes, avec implications directes pour la gestion urbaine. Le nord et le centre de l'Europe montrent une intensification du cycle hydrologique, caractérisée par une hausse des précipitations totales et des extrêmes, tandis que la région méditerranéenne présente des tendances à l'allongement des périodes de sécheresse. En Amérique latine, une hétérogénéité spatiale se dégage : la Colombie, le Pérou et le sud du Brésil enregistrent une augmentation des précipitations, alors que le centre du Brésil connaît une réduction significative des totaux pluviométriques. L'analyse des 20 plus grandes métropoles révèle qu'une augmentation généralisée des extrêmes de précipitations représente un défi majeur pour les infrastructures urbaines. Une configuration particulièrement préoccupant émerge dans des villes latino-américaines comme São Paulo, Belo Horizonte, Medellín et Fortaleza, qui présentent une augmentation concomitante des événements extrêmes et des jours secs, contrastant avec les villes européennes où les extrêmes s'accompagnent d'un régime plus humide.

ABSTRACT

Urban drainage systems designed under assumptions of climate stationarity face mounting challenges due to changing precipitation patterns. This study assesses trends in five indices critical for the design and operation of urban water infrastructure—1-day and 3-day maximum precipitation, dry days, total annual precipitation, and wet-season variability—using data from 24,585 rain gauge stations across Latin America and Europe (1900–2024). Results reveal distinct regional patterns with direct implications for urban management. Northern and Central Europe show an intensification of the hydrological cycle, characterized by increased total precipitation and extremes, while the Mediterranean exhibits trends toward prolonged droughts. In Latin America, spatial heterogeneity is evident: Colombia, Peru, and Southern Brazil show increased precipitation, whereas Central Brazil presents a significant reduction in rainfall totals. Analysis of the 20 largest metropolitan areas indicates that a widespread increase in precipitation extremes poses a critical challenge for urban infrastructure. Of particular concern is the pattern observed in Latin American cities such as São Paulo, Belo Horizonte, Medellín, and Fortaleza, which display a concurrent rise in both extreme events and dry days, contrasting with European cities where extremes are accompanied by a wetter regime.

KEYWORDS

Climate change; Precipitation trends; Urban water management; Non-stationarity ; Metropolitan adaptation

1 INTRODUCTION

Urban drainage infrastructure faces unprecedented challenges due to global shifts in precipitation patterns. Systems designed under the assumption of climate stationarity—where extreme design events are estimated from historical series deemed representative of the future—risk becoming progressively inadequate as rainfall regimes shift (Salas et al., 2018). This paradigm shift requires not only the assessment of changes in precipitation patterns but also the characterization of how these changes manifest across different regions and their practical implications for the design, operation, and adaptation of urban water systems.

Shifts in rainfall regimes impact multiple facets of urban water management. Increased intensity of extreme events can overload drainage systems designed for lower peak flows, leading to more frequent and severe urban flooding. Concurrently, prolonged dry spells compromise water supply, while seasonal variability complicates integrated planning and reservoir operation (Fletcher et al., 2013; Tobin et al., 2018).

Growing evidence documents significant regional shifts in precipitation patterns demanding differentiated adaptation strategies (IPCC, 2021). In Europe, northern regions experience hydrological cycle intensification with increased total precipitation and extremes (André et al., 2024), while the Eastern Mediterranean exhibits warming rates nearly double the global average (Zittis et al., 2022), resulting in increased dry day frequency (Christidis & Stott, 2022). Central Europe shows intermediate patterns, including monthly precipitation reductions affecting aquifer recharge rates (Ionita et al., 2020).

Latin American patterns are equally complex and heterogeneous. The Brazilian Cerrado shows reductions exceeding 300 mm/year (Hofmann et al., 2023), while the Amazon has recorded approximately one-month dry season extensions since the 1970s (Marengo et al., 2015). In the tropical Andes, reduced wet-season precipitation compromises water supply for metropolises such as Lima and Bogotá (Vuille et al., 2018). The Pacific coast observes intensified El Niño-associated extreme events (Lavado-Casimiro et al., 2012), Northeast Brazil documents drying trends (Marengo et al., 2018), and the La Plata Basin shows increases in both total annual precipitation and extreme events, elevating flood risks (Barros et al., 2015).

Despite regional knowledge advances, urban water practitioners lack comparative analyses contextualizing local changes within broader continental patterns. Most studies focus on isolated regional analyses limited to total precipitation, without systematically evaluating multiple indicators relevant to drainage assessment such as maximum intensities, dry spells, and seasonal variability. This gap is critical because different indicators carry distinct infrastructure implications: 1- to 3-day maximum precipitation affects structural design; dry day changes impact reuse and rainwater harvesting strategies; and seasonal variability shifts affect integrated system operation (Fletcher et al., 2013; Kuller et al., 2020).

Therefore, this study characterizes and compares temporal trends in precipitation indicators across Latin America and Europe, utilizing data from over 24,000 rain gauge stations. Specifically, we: (i) analyze trends in 1-day and 3-day maximum precipitation, dry day sequences, total annual precipitation, and wet-season variability; (ii) identify spatial patterns at continental scale; and (iii) assess implications for urban water management in major metropolitan centers.

2 METHODS

This study utilized daily precipitation data from rain gauge stations across Latin America and Europe, spanning the period from 1900 to 2024. For Latin America, data were sourced from Brazil's National Water Agency (ANA) and the Global Historical Climatology Network (GHCN-Daily). For Europe, data were obtained from the European Climate Assessment & Dataset (ECA&D) (Klein Tank et al., 2002). Stations were selected based on: (i) minimum 30-year time series; and (ii) maximum 20% missing data per year. Daily records exceeding 300 mm were verified through comparison with the five nearest stations (Salviano et al., 2016). Monthly coefficients of variation and mean annual precipitation are presented in Figure 1.

For each station, five annual indices were calculated: (i) 1-day and 3-day consecutive maximum precipitation; (ii) number of dry days and longest continuous dry spell (precipitation < 1 mm); (iii) total annual precipitation; and (iv) standard deviation of daily precipitation during the wet season. The Mann-Kendall (Mann, 1945; Kendall, 1975), Spearman, and Pettitt (Pettitt, 1979) non-parametric tests were applied to detect monotonic trends and abrupt changes. Following recent recommendations (Wasserstein et al., 2019), p-values were treated as continuous descriptive statistics, integrating magnitude (Kendall's Tau), direction of change, and spatial coherence patterns.

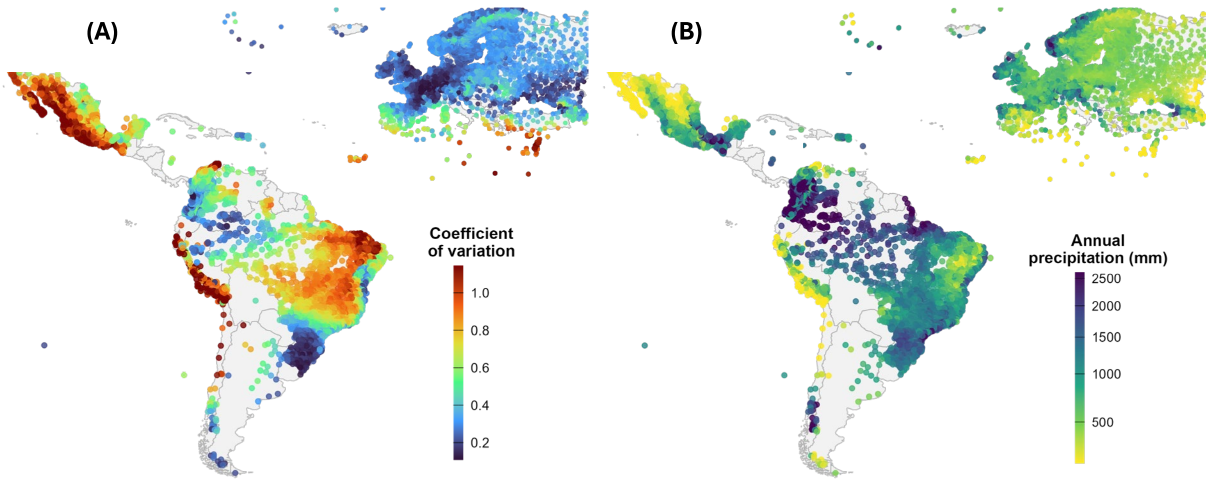

Figure 1 : Indicadores de todas as estações em : (A) Coeficiente de variação mensal ; e (B) Precipitação média anual

Following recent recommendations (Wasserstein et al., 2019), p-values were treated as continuous descriptive statistics. The analysis integrated magnitude (Kendall's Tau), direction of change, and spatial patterns of regional coherence. Serial autocorrelation was not explicitly addressed; however, it is recognized that analyzing extensive station networks enables the identification of spatially coherent patterns (Wilks, 2006).

To assess impacts on major urban areas, the GHS-FUA database (Schiavina et al., 2019) was used to identify the top 20 metropolitan regions by population. All rain gauge stations within 100 km of metropolitan boundaries were analyzed to characterize the predominant direction of change for each index.

3 RESULTS

The obtained results are summarized in Figure 2 and Table 1 for the major metropolitan regions.

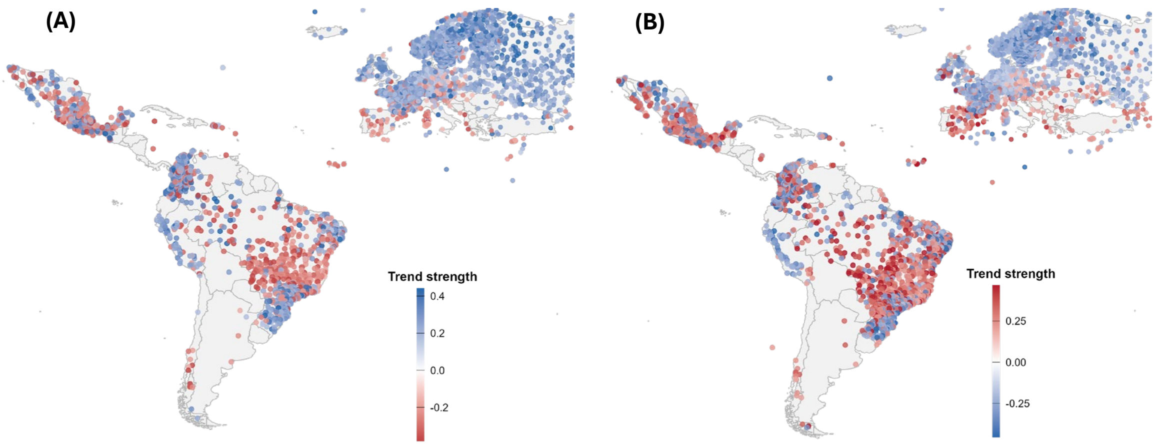

Figure 2 : Stations showing trends, color-coded by direction of change: (A) Total annual precipitation; (B) Annual dry days.

4 DISCUSSION AND CONCLUSION

The results reveal contrasting regional patterns between Latin America and Europe. European stations show generalized hydrological cycle intensification, particularly in northern regions with increased annual precipitation, reduced dry days, and intensified extremes (especially 3-day maxima). Central Europe exhibits similar but less intense patterns, while the Mediterranean trends toward a drier regime with reduced annual precipitation and increased dry spells. In Latin America, patterns are more heterogeneous: Colombia, Peru, and Southern Brazil show increased annual precipitation, whereas Central Brazil presents concerning reductions in annual totals concurrent with increases in extremes and dry days.

Analysis of major metropolitan areas reveals that widespread increases in precipitation extremes pose critical challenges for urban drainage infrastructure designed under stationary rainfall assumptions. Particularly concerning is the pattern in São Paulo, Belo Horizonte, Medellín, and Fortaleza, where simultaneous increases in extreme events and dry days create compounded flooding and water scarcity risks. This pattern contrasts with Central European metropolises such as Hamburg, Munich, Vienna, Frankfurt, Brussels, and Rotterdam, where the increase in extremes is generally accompanied by wetter conditions.

City	Populat. (M)	Daily Maxima	Dry days	Annual Precip.	Variability	Synthesis
São Paulo	21.7	↑	↓	↑	↑	Increasing annual totals and daily extremes; drying trend
Mexico City	21.4	↑	↑	-	↑	Increase in daily extremes and dry days; stable annual totals
London	12.6	-	↑	↑	-	Increasing annual totals; more dry days
Paris	11.2	↑	↓	↑	↑	Increasing annual totals and daily extremes; wetter conditions
Rio de Janeiro	10.8	-	↑	-	↑	Drying trend; higher variability
Lima	9.7	-	↑	-	-	Trend towards increased dry days
Bogotá	9.1	↑	↓	↑	↑	Increasing annual totals and daily extremes; wetter regime
Belo Horizonte	5	↑	↑	↓	↑	Decreasing annual totals; increasing extremes and daily variability
Barcelona	4.6	-	↑	↓	-	Decreasing annual totals; more dry days
Berlin	4.3	↑	↓	↑	-	Increasing annual totals and daily extremes
Medellín	3.6	↑	↑	↑	↑	Generalized intensification with higher variability
Fortaleza	3.6	↑	↑	-	↑	Increasing daily extremes and number of dry days; higher variability
Curitiba & Cali	5.4	↑	-	↑	↑	Increasing annual totals, daily extremes, and variability
Rotterdam, Frankfurt, Hamburg, Munich, Vienna & Brussels	16.3	↑	↓	↑	↑	Increasing annual totals and daily extremes; wetter conditions

Table 1: Summary of results for major urban centers.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes).

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