EDITORIAL



# Climate change and urbanization inducing a tipping point in the hydrosphere

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Since April 2024, extreme flood events in South China, South England and the Persian Gulf have resulted in thousands of people being displaced and tens of millions of dollars in economic losses, once again sparking significant concerns. As one of the tipping points in the hydrosphere, the exacerbating floods under climate change have posed a global threat to human societies and ecosystems.[1] Meantime, urban areas are increasingly vulnerable region to extreme floods due to rapid urbanization and intense anthropogenic activities. This further exacerbates inequalities and presents a challenge to sustainable development.

In response to these challenges, effective flood risk management under changing environments has emerged as a pivotal task within the ambit of the United Nations Sustainable Development Goals (UN-SDGs), as it significantly

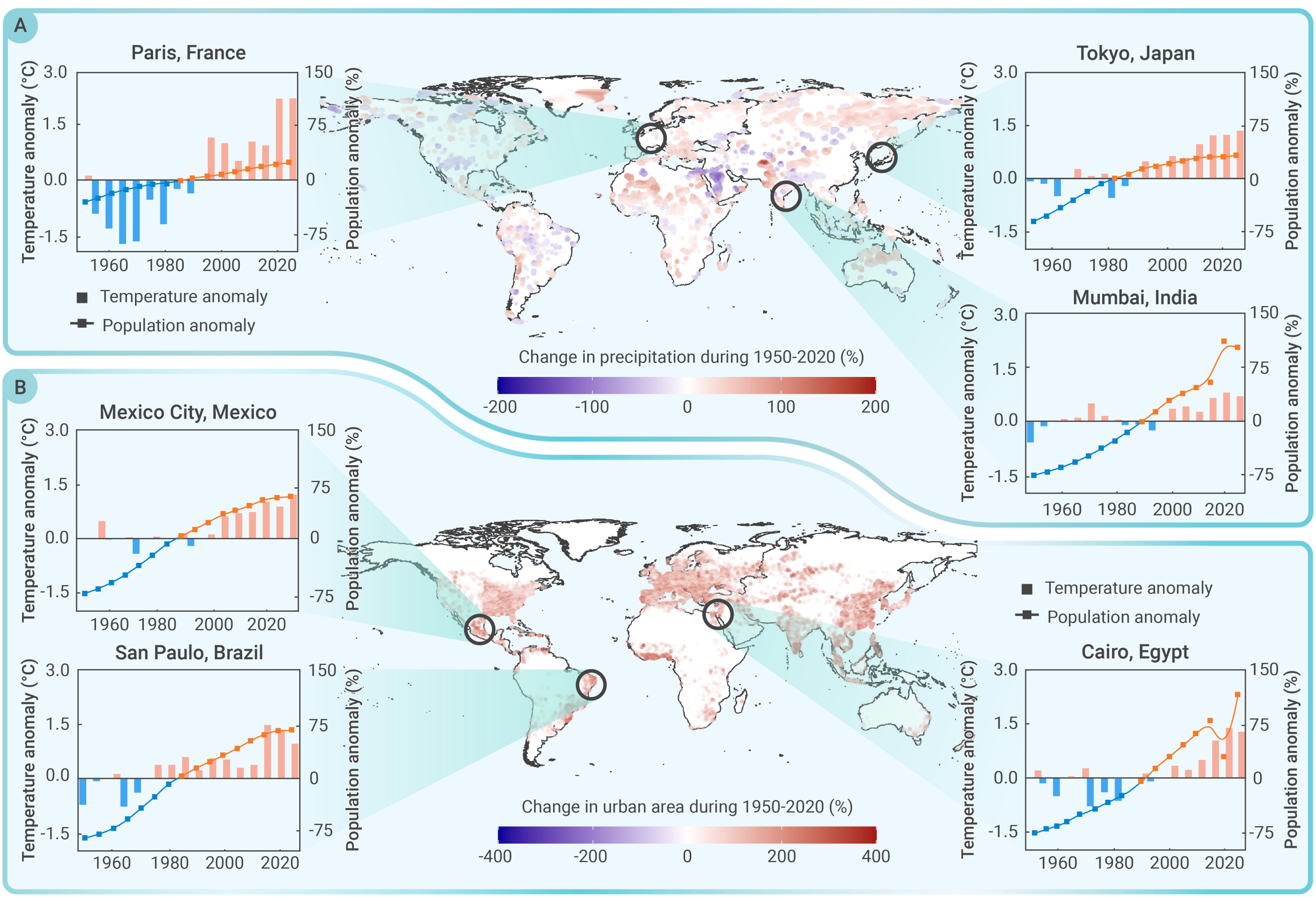


Figure 1. Changes in precipitation (A) and urban area (B), with temperature and population anomalies of megacities

affects the well-being of human societies (UN-SDG3), the health of ecosystems (UN-SDG14, 15), and the inequality across regions (UN-SDG10).[2] However, the complex cascading effects of climate change and urbanization on regional hydrology cause spatiotemporal heterogeneity of extreme floods, posing challenges to flood risk management. To address these issues, it is imperative to reveal the influencing mechanisms of climate change and urbanization on flood heterogeneity, and accordingly propose coping strategies within an evolving environmental context.

## CLIMATE CHANGE INDUCE FLOOD HETEROGENEITY

Climate change impacts the hydrological regime during both wet- and dry-weather periods, which leads to heterogeneity in flood generation. Over the past decades, most of the global land has experienced more frequent extreme precipitation events. As demonstrated in Figure 1A, a significant increase in precipitation has been observed in East Asia, the Caribbean, and Sub-Saharan, this directly amplifies surface runoff. Conversely, in regions such as West Asia, North Africa, and the Amazon, the precipitation has exhibited a downward trend, implying a prolonged antecedent dry period. The prolonged and intensive drought events compromise the infiltration and moisture retention capacities of topsoil, resulting in heightened runoff peak flows during subsequent wet-weather periods, thereby heightening the probability and severity of flash floods.

In addition, the temperature rise induced by climate change further catalyzes flood heterogeneity from both temporal and spatial perspectives. In terms of time, a warmer climate leads to a decrease in snow depth, thereby directly reducing the occurrence of snowmelt-induced floods during spring in several regions, like the Mediterranean and the Central Alpine.[3] Concurrently, escalated rates of evaporation under climate change contribute to the increased flooding due to soil drought during other seasons. This not only disruptes the temporal distribution of flood occurrences, but also alters the relative contributions of diverse factors to flood genesis, thus posing a challenge to targeted flood risk mitigation strategies. In terms of space, a warmer climate would change atmospheric circulation trends across the globe. For instance, the weakening of the Atlantic meridional overturning circulation (AMOC) due to rising temperature, which is proven to be one of the tipping points in the climate system, would accelerate the sea level rise in North America and decrease the precipitation in Europe. This not only exacerbates the spatial heterogeneity of flood risks, but also causes significant impacts on ecosystems through fluctuations in water quantity and quality.

## URBANIZATION EXACERBATE FLOOD HETEROGENEITY

Disproportionate urbanization has led to significant changes in land use patterns, resulting in flood heterogeneity across regions. During the past decades, over 290,000 $km^2$ of natural spaces have been converted into urban lands across the globe, which tripled the proportion of impervious covers. Among them, some urban areas in East Asia, Western Europe, and North America have increased by over 200%, as shown in Figure 1B.The expanded impervious covers in these regions impede the infiltration of precipitation into the natural soil, thereby amplifying the surface runoff and peak flow. This would bring greater pressure to the local drainage system, which raises the susceptibility to waterlogging due to system failure. Concurrently, the amplified runoff will intensify the flushing effect of the bare soil. This exacerbates soil erosion and further compromises the infiltration capacity of the natural soil, eventually leading to an increase in surface runoff and flood risk.

Additionally, population growth during urbanization contributes to the urban heat island (UHI) effect, which exacerbates the flood heterogeneity between urban and rural areas. The growing population brings increased anthropogenic heat emissions, more dense buildings, and reduced evaporative cooling. This causes the higher local average air temperature than that in surrounding rural areas, referring to the UHI effect. As of 2023, over 4.61 billion of the world's population are currently living in urban areas. In some megacities, such as Tokyo, Cairo, Paris, and Sao Paulo, the inhabitants have rapidly increased since 1950, inducing significant UHI effects (temperature rise by approximately 1.5ºC) over the past decades, as shown in Figure 1. The UHI effect not only brings high temperatures, but also enhances the frequency and intensity of localized convective precipitation. More explicitly, the low-pressure area created by the UHI effect would stimulate the convergence of moist air in urban areas, and the extra heat from UHI would accelerate air expansion, uplift, and condensation, eventually resulting in convective precipitation. Characterized by their intense precipitation rates but short durations, these convective precipitation events bring challenges to urban drainage systems in addressing high runoff peaks in time, which would heighten the risk of acute inundation incidents.

## COPING STRATEGIES TO FLOOD HETEROGENEITY

Given the exacerbated flood heterogeneity under the cascading effects of climate change and urbanization, it is essential to address these challenges from the perspectives of early warning systems and resilience coping strategies.[4] In this regard, hydrological modeling has been identified as one of the major components of the early warning system. However, the traditional modeling approach is encountering challenges in terms of big-data processing and computational load. On the one hand, the lack of long-term records in some regions limits the applicability of hydrological modeling. Although the fusion of multi-source data (e.g., remote sensing, social media data, general circulation model projection) has addressed this limitation to some extent, the identification of crucial hydrological information from massive datasets with varied structures is still a key challenge. On the other hand, within the context of urbanization, there is a growing demand for high-resolution modeling to capture the complexities of evolving urban environments. Given that large-dataset processing and high-resolution modeling are computationally expensive and time consuming, this would pose challenges in modeling-based early warning of floods. Concerning this issue, coupling artificial intelligence (AI) with the existing modeling approach would be a promising solution. By analyzing historical floods and related data (meteorological, hydrological, topographical) through algorithms including deep learning, neural networks, long-short term memory, etc., the AI captures the crucial features with the most relevance to flooding, thereby providing additional support in revealing the flood generation and migration patterns in different regions ( gauged and ungauged).

Moreover, some institutional coping strategies are demanded for flood risk management under changing environments. On the one hand, nature-based solution (NbS), also termed Low Impact Development in the US, Green Infrastructure in Europe, and Sponge City in China, promotes runoff infiltration and retention through decentralized infrastructures, thereby enhancing the system resilience in response to climate change-induced flood risk. Furthermore, the increased vegetation brought by NbS benefits evaporative cooling and facilitates heat removal in urban areas, thereby alleviating the UHI effect and associated flood risk. On the other hand, sustainable urbanization policy plays a vital role in flood risk management. At the national level, it is necessary to focus on coordinated development across regions, thereby avoiding the emergence of megacities and the gathering of large populations. For urban planning practitioners, it is meaningful to balance the impervious surfaces and blue-green infrastructures in urban areas, thereby ensuring sufficient runoff infiltration and evapotranspiration effects. In this regard, the STEP framework facilitates the synergy and balance of these strategies by integrating science, technology, engineering and policy.[5]

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## DECLARATION OF INTERESTS

The authors declare no competing interests.