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Urban Heat Island Intensification and Its Feedback on Convective Storm Initiation in Tropical Megacities

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Abstract— *Rapid urbanization across tropical megacities has intensified the Urban Heat Island (UHI) effect, altering not only local thermal comfort but also the boundary-layer dynamics that govern convective storm initiation. Unlike mid-latitude UHI studies, tropical megacities operate in a high-humidity, high-instability background environment in which even modest urban-induced thermal and mechanical perturbations can trigger disproportionately large convective responses. This paper examines the coupling between UHI intensification and convective storm initiation across tropical megacities including Mumbai, Jakarta, Manila, and São Paulo, synthesizing evidence from urban boundary-layer observations, dual-polarization radar climatologies, and coupled urban-canopy/mesoscale model simulations. The review addresses three physical pathways linking urbanization to convective enhancement: urban-induced differential heating that generates thermally driven convergence zones, aerosol-mediated microphysical modification of cloud droplet spectra, and urban surface roughness effects that alter low-level convergence and boundary-layer depth. A comparative methodology is described using Weather Research and Forecasting model coupled with an Urban Canopy Model (WRF-UCM), satellite-derived land surface temperature (LST) retrievals, and Tropical Rainfall Measuring Mission (TRMM)/Global Precipitation Measurement (GPM) precipitation climatologies to isolate urban rainfall signatures from background convective variability. Reported findings across the reviewed literature consistently indicate a statistically significant downwind and over-city enhancement of afternoon convective rainfall frequency and intensity attributable to urban land-use change, though the magnitude and spatial pattern of this enhancement vary considerably with city morphology, background synoptic forcing, and coastal proximity. The paper concludes by identifying key uncertainties in aerosol-convection interaction representation, urban-canopy parameterization resolution, and the compounding risk of urban flash flooding arising from UHI-enhanced convection over increasingly impervious urban surfaces.*

Keywords— Urban Heat Island, Convective Initiation, Tropical Megacities, Urban-Induced Precipitation, Land-Atmosphere Coupling, Urban Canopy Model, Aerosol-Cloud Interaction, Mesoscale Convection.

I. INTRODUCTION

Tropical megacities, defined as urban agglomerations exceeding ten million inhabitants located within the tropical belt, have expanded at unprecedented rates over the past three decades, converting natural vegetated and coastal land cover into extensive impervious surfaces [1]. This land-use transformation alters the surface energy balance, replacing evapotranspiration-dominated latent heat flux with sensible heat flux driven by low-albedo, low-thermal-inertia construction materials, producing the well-documented Urban Heat Island (UHI) effect in which city-center temperatures exceed surrounding rural temperatures, often by 2–7°C during nocturnal hours in tropical settings [2].

While UHI research has historically focused on mid-latitude cities and its implications for heat-related mortality and energy demand, tropical megacities present a distinct dynamical regime because the background atmosphere is already close to convective instability thresholds due to high ambient temperature and moisture content [3]. In this regime, even a modest urban-induced enhancement of near-surface buoyancy or low-level convergence can be sufficient to trigger convective initiation that would not otherwise occur, or to intensify convection that does occur, producing a measurable urban rainfall signature superimposed on the natural tropical convective climatology [4].

Observational evidence for urban-induced convective modification has accumulated substantially since early studies using rain-gauge networks around Houston and other mid-latitude cities identified statistically significant rainfall enhancement downwind of the urban core, attributed to a combination of thermal, aerosol, and mechanical forcing mechanisms [5]. Subsequent research using the Tropical Rainfall Measuring Mission (TRMM) satellite precipitation radar extended this analysis to a global sample of cities, finding a broadly consistent pattern of enhanced precipitation frequency and intensity downwind of major urban areas, with the effect being more pronounced in warm, humid climates than in arid ones [6].

Three physical mechanisms are commonly invoked to explain this urban-convection coupling. First, the urban heat island generates a thermally direct mesoscale circulation, analogous to a sea breeze, in which air converges toward the warmer urban core, lifts, and can reach the level of free convection under marginally unstable ambient conditions [4]. Second, elevated urban aerosol concentrations, arising from vehicular and industrial emissions, modify cloud condensation nuclei (CCN) concentrations, altering droplet size distributions in a manner that has been linked in several studies to invigorated convective updrafts and delayed but more intense precipitation, through the so-called aerosol invigoration effect, although this mechanism remains more contested than the thermal pathway [7]. Third, increased surface roughness from building geometry enhances mechanically induced low-level convergence and modifies boundary-layer turbulence structure, independently of thermal forcing, contributing to localized convective triggering near roughness discontinuities such as the urban-rural boundary [8].

Regional studies focused specifically on tropical megacities have reinforced these findings. Radar and rain-gauge analyses over Mumbai identified a statistically significant increase in the frequency of intense, short-duration convective rainfall events over and downwind of the urban core during the pre-monsoon and monsoon-onset periods, coincident with rapid urban expansion over the preceding two decades [9]. Comparable urban rainfall enhancement signatures have been documented for Jakarta [10] and for coastal megacities in China where the urban-sea-breeze interaction further complicates the convective response [11].

Coupled mesoscale modeling using the Weather Research and Forecasting model with an embedded Urban Canopy Model (WRF-UCM) has provided process-level evidence supporting the thermally driven convergence mechanism, demonstrating in simulation experiments that removing urban land-use characteristics and replacing them with natural land cover substantially reduces simulated afternoon convective initiation frequency over the urbanized domain [12]. However, these same modeling studies emphasize that skill in reproducing urban-convection feedback remains highly sensitive to urban canopy parameterization choices, model horizontal resolution, and the representation of anthropogenic heat flux, introducing substantial uncertainty into quantitative attribution [13].

The societal stakes of this feedback are considerable: UHI-enhanced convective initiation over tropical megacities compounds urban flash-flood risk because the same impervious surfaces that intensify the UHI also reduce infiltration capacity, meaning that urbanization simultaneously increases the likelihood of intense convective rainfall and the surface's vulnerability to that rainfall [14]. This compounding risk motivates the present review.

While several excellent reviews have addressed urban-induced precipitation effects more broadly (Shepherd, 2005; Roth, 2007), the specific context of tropical megacities—where high background humidity and instability make the urban-convection coupling particularly sensitive—has not been comprehensively synthesized. Furthermore, existing reviews have not systematically compared mechanistic pathway contributions across multiple tropical cities nor explicitly linked UHI-convection enhancement to compounding flood risk. This review addresses these gaps by providing a unified synthesis that: (1) focuses specifically on tropical megacities, (2) systematically compares observed enhancement patterns across Mumbai, Jakarta, Manila, and São Paulo, (3) critically evaluates the relative contributions of thermal, aerosol, and mechanical pathways, and (4) explicitly connects urban-convection findings to compounded flood-risk implications for urban planning.

1.1 Research Objectives

1) To examine the physical mechanisms linking urban heat island intensification to convective storm initiation in tropical megacities.
2) To review observational and satellite-based evidence of urban-induced precipitation modification across major tropical megacities.

3) To evaluate coupled urban-canopy/mesoscale modeling approaches used to attribute convective enhancement to urbanization.
4) To compare reported spatial patterns and magnitudes of urban rainfall enhancement across cities and climate regimes.
5) To identify uncertainties and compounding flood-risk implications of UHI-convection feedback for urban planning.

II. LITERATURE REVIEW

2.1 Urban Heat Island Characteristics in Tropical Settings

The UHI effect arises from the replacement of vegetated, high-albedo, high-thermal-inertia natural surfaces with low-albedo, high-heat-capacity construction materials that store daytime solar radiation and release it as sensible heat, particularly during nocturnal hours [2]. In tropical megacities, this effect is compounded by generally lower wind speeds associated with monsoonal or trade-wind regimes during convective seasons, reducing horizontal ventilation of the urban heat plume and allowing UHI intensity to accumulate through the afternoon [3]. Satellite-derived land surface temperature (LST) retrievals over Indian, Southeast Asian, and South American megacities have consistently shown urban-rural LST differences of 3–8°C during peak daytime hours, with the magnitude scaling with the extent of impervious surface cover and inversely with residual green space fraction [9], [10].

The diurnal evolution of the UHI in tropical settings deserves particular attention. Unlike mid-latitude cities where the UHI typically peaks several hours after sunset, tropical megacities often exhibit a persistent daytime UHI due to high solar radiation throughout the year and limited seasonal variation in day length. This persistent daytime heating, combined with high background humidity, means that urban-induced thermal perturbations are present during the peak convective hours of the afternoon, directly enhancing the likelihood of urban-triggered convection [3].

2.2 Thermally Driven Urban Convergence Mechanism

The dominant mechanism proposed for urban-induced convective initiation is a thermally direct, sea-breeze-like circulation in which differential heating between the urban core and surrounding rural or vegetated land generates a horizontal pressure gradient, drawing near-surface air toward the city center [4]. Under marginally unstable tropical atmospheric profiles, this urban-induced convergence can be sufficient to lift parcels to the level of free convection, triggering convective initiation earlier in the diurnal cycle and preferentially over or immediately downwind of the urban core, consistent with the general finding that urban rainfall anomalies are typically displaced 10–50 km downwind of the city center in the direction of the prevailing low-level flow [5], [6].

The strength of this thermally driven circulation depends on several factors: the magnitude of the urban-rural temperature gradient (which scales with UHI intensity), the static stability of the background atmosphere (lower stability allowing more vigorous ascent), and the depth of the boundary layer (which determines the vertical extent of the perturbation). In tropical settings, high humidity reduces the temperature difference required to initiate convection, meaning that a smaller thermal perturbation can trigger a convective response than in drier mid-latitude environments [3].

2.3 Aerosol-Mediated Microphysical Pathways

Urban aerosol loading, dominated by combustion-derived particulate matter, has been proposed as a secondary but influential pathway by which cities modify convective behavior. Increased CCN concentrations tend to produce numerous smaller cloud droplets that are less efficient at initiating warm-rain collision-coalescence processes, delaying the onset of precipitation but allowing convective updrafts to transport greater condensate mass to higher, colder levels, where ice-phase processes can release additional latent heat and invigorate the storm, a mechanism generally referred to as aerosol invigoration [7]. This pathway remains more contested than the thermal mechanism because its net effect depends strongly on background aerosol concentration, humidity, and wind shear, with some studies reporting convective suppression rather than invigoration under very high aerosol loading conditions, indicating a non-monotonic relationship between aerosol concentration and convective intensity [15].

Specifically, the aerosol invigoration effect is most pronounced under conditions of moderate aerosol loading, where the suppression of warm-rain processes allows more cloud water to reach the mixed-phase region, releasing latent heat and invigorating updrafts. Under very high aerosol loading, however, the sheer abundance of CCN can produce so many small droplets that they compete for available moisture, suppressing the formation of precipitation entirely. This non-monotonic relationship—sometimes described as an "inverted U" response—means that the net effect of urban aerosol emissions on convection depends strongly on the background aerosol concentration and the prevailing meteorological conditions.

2.4 Surface Roughness and Mechanical Forcing

Urban building geometry substantially increases effective surface roughness relative to natural terrain, altering boundary-layer turbulence characteristics and generating localized zones of enhanced low-level convergence near abrupt urban-rural roughness transitions, independent of any thermal forcing [8]. This mechanical pathway has been shown in idealized modeling studies to contribute to convective triggering even under near-neutral thermal contrast conditions, suggesting that urban morphology, including building height variability and street canyon orientation, exerts an independent influence on convective initiation location beyond that attributable to the UHI temperature signal alone [8].

The mechanical pathway operates through several mechanisms. First, the increased aerodynamic roughness of urban surfaces enhances turbulent mixing, deepening the boundary layer and potentially raising the lifting condensation level. Second, the frictional convergence at the urban-rural boundary, analogous to the convergence generated by changes in surface vegetation, can provide the lifting required to initiate convection. Third, the heterogeneity of building heights within the urban fabric generates localized zones of enhanced turbulence that can further promote convective triggering. Studies of Beijing and other Asian megacities have shown that the mechanical effect can contribute substantially to urban-induced convection, even under thermally neutral conditions [8].

2.5 Evidence from Tropical Megacity Case Studies

Radar-based rainfall climatologies over Mumbai identified a statistically significant increase in the frequency of high-intensity, short-duration rainfall cells during the pre-monsoon period over the urbanized region relative to the surrounding Konkan coastal belt, with the effect strengthening over the period of most rapid urban expansion between the early 1990s and the late 2000s [9]. The Mumbai enhancement is particularly pronounced during the monsoon onset period (late May to June), when the background atmosphere is highly unstable and the prevailing westerly winds favor downwind rainfall enhancement over the city's eastern suburbs.

Comparable analyses over the Jakarta metropolitan area found enhanced afternoon convective rainfall frequency downwind of the urban core, complicated by the interaction between the urban heat island circulation and the sea-breeze circulation associated with Jakarta's coastal location, producing a convergence zone whose position shifts diurnally and seasonally [10]. In Jakarta, the interaction between the land-sea breeze and the urban-induced circulation can either amplify or reduce convective enhancement depending on the phase alignment of the two circulations.

For Manila, studies have shown that the urban heat island enhances convective rainfall during the southwest monsoon (June to October), with the enhancement most pronounced over the urban core and downwind regions, although the effect is modulated by the complex coastal geometry and the presence of surrounding water bodies [16]. The Manila case exemplifies how coastal geometry and sea-breeze interaction can either amplify or dampen the urban convective response.

For São Paulo, while extensive observational studies are somewhat limited relative to the Asian cities, available evidence indicates a statistically significant urban-induced enhancement of convective rainfall during the austral summer (November to March), with the signature most pronounced over the city's eastern and southern suburbs, consistent with the prevailing wind direction [16]. This finding suggests that the UHI-convection coupling is a robust phenomenon across diverse tropical settings.

Studies of coastal Chinese megacities similarly report that urban-sea-breeze interaction can either amplify or suppress urban rainfall enhancement depending on the relative timing and phase alignment of the two circulations, underscoring the importance of city-specific coastal geometry in determining the net convective response [11].

2.6 Modeling Evidence and Attribution

Coupled WRF-UCM simulation experiments, in which urban land-use categories are systematically replaced with natural vegetated land cover in sensitivity runs, have demonstrated that urbanization measurably increases simulated afternoon convective initiation frequency and total precipitation over the urbanized domain relative to the naturalized control run, providing process-level attribution evidence consistent with the thermally driven convergence mechanism [12]. However, these studies also report that simulated urban rainfall enhancement magnitude is highly sensitive to the choice of urban canopy parameterization (single-layer vs. multi-layer schemes), horizontal grid resolution, and specified anthropogenic heat flux magnitude, with coarser-resolution simulations tending to underestimate the spatial concentration of urban-induced convective triggering [13].

The sensitivity of modeled results to parameterization choices has important implications for attribution confidence. Studies using convection-permitting resolution (horizontal grid spacing below approximately 3 km) have demonstrated substantially better agreement with observed rainfall patterns than coarser-resolution studies, which necessarily parameterize convective processes. Similarly, multi-layer urban canopy schemes that explicitly resolve building-height-dependent heat storage and roughness effects produce more realistic urban-convection interactions than single-layer schemes. Anthropogenic heat flux specification, which varies with emission sources and diurnal patterns, is another critical factor; studies that include realistic anthropogenic heat fluxes generally simulate stronger UHI-convection coupling than those that neglect this forcing.

2.7 Research Gap

Although substantial evidence supports urban-induced convective enhancement in both mid-latitude and tropical settings, most process-attribution modeling studies remain city-specific, and cross-city comparative synthesis, particularly across differing tropical megacity morphologies (coastal vs. inland, monsoonal vs. equatorial), remains limited [9]–[11]. Furthermore, the relative contribution of thermal, aerosol, and mechanical pathways is rarely disentangled within a single observational or modeling framework, and existing studies seldom explicitly connect urban-convection enhancement findings to compounding flash-flood risk arising from simultaneously reduced infiltration capacity [14].

Additionally, while the basic UHI-convection coupling has been documented across multiple cities, there remain significant gaps in understanding of how this coupling may change under future climate scenarios, how it interacts with different urban morphologies, and what the quantitative implications are for urban flood-risk assessments. This study addresses these gaps by synthesizing evidence across all three mechanistic pathways and multiple tropical megacity case studies within a unified comparative framework.

III. METHODOLOGY

3.1 Research Design

This study adopts a qualitative, descriptive, and comparative research design based on synthesis of observational, satellite-remote-sensing, and coupled mesoscale modeling literature addressing UHI-convection interactions in tropical megacities. Rather than generating new simulation output, the research consolidates reported findings across multiple methodological approaches to identify consistent mechanistic patterns and quantify the range of reported urban convective enhancement magnitudes.

3.2 Literature Search Strategy

A systematic literature search was conducted using major scientific databases including Web of Science, Scopus, and Google Scholar. Search terms included combinations of "Urban Heat Island," "convective initiation," "tropical megacities," "urban-induced precipitation," "land-atmosphere coupling," "urban canopy model," and "aerosol-cloud interaction." The search was restricted to peer-reviewed English-language publications from 1980 to 2025. Additionally, reference lists of identified review articles were hand-searched to identify relevant studies not captured by database searches. Grey literature and conference abstracts were not included unless subsequently published as peer-reviewed articles.

3.3 Inclusion and Exclusion Criteria

Studies were included if they: (1) addressed UHI-convection coupling in tropical or subtropical settings; (2) presented original observational data, satellite analyses, or modeling results; (3) quantified some aspect of urban-induced rainfall modification; and (4) were published in peer-reviewed journals. Studies were excluded if they: (1) focused exclusively on mid-latitude or extratropical cities; (2) addressed UHI effects on temperature only without convective implications; or (3) were not available in English.

3.4 Conceptual Framework

The framework applied in this review models UHI-convection feedback as a three-pathway system converging on convective initiation likelihood. Urban land-use change modifies the surface energy balance, producing (1) a thermal pathway via differential heating and thermally direct convergence, (2) an aerosol pathway via CCN modification and updraft invigoration, and (3) a mechanical pathway via surface roughness-induced convergence. These pathways jointly influence boundary-layer depth, low-level convergence intensity, and moisture availability, determining whether ambient tropical instability is realized as convective initiation over or downwind of the urban core, with the resulting rainfall further influencing urban flash-flood risk through interaction with impervious surface runoff characteristics.

3.5 Data Sources

The literature synthesized in this review draws on satellite-derived land surface temperature retrievals (Landsat Thermal Infrared Sensor, MODIS LST products) for UHI characterization; Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) satellite precipitation radar climatologies for urban rainfall signature detection; ground-based Doppler and dual-polarization radar networks for high-resolution convective cell tracking over specific megacities; and coupled Weather Research and Forecasting model with Urban Canopy Model (WRF-UCM) sensitivity experiments for process-level mechanistic attribution.

3.6 Analytical Framework for Urban Rainfall Signature Detection

Studies reviewed typically isolate the urban rainfall signal using one of two complementary approaches: (1) spatial composite analysis, comparing precipitation frequency and intensity statistics in concentric distance bands around the urban core against a rural reference region matched for background synoptic forcing, and (2) paired sensitivity modeling, comparing simulated convective behavior between an urbanized land-use configuration and a naturalized control configuration under otherwise identical initial and boundary conditions [12]. Both approaches require careful control for confounding factors including coastal proximity, orographic influence, and prevailing synoptic-scale forcing, since these can independently produce spatial rainfall gradients that mimic an urban signature.

3.7 Evaluation Criteria

Comparative evaluation in this review uses four metrics standard in the urban precipitation literature: rainfall frequency anomaly (percentage change in convective event frequency over/downwind of the urban core relative to the rural reference), rainfall intensity anomaly (change in mean or extreme precipitation rate), spatial displacement distance (downwind offset of the peak rainfall anomaly from the urban center), and UHI intensity (urban-rural LST or near-surface temperature difference), used to assess whether reported convective enhancement scales with the magnitude of urban thermal perturbation across studies.

3.8 Quality Assessment

Given the heterogeneity of methods and study designs across the reviewed literature, a narrative synthesis approach was adopted. Studies were assessed for methodological quality based on: (1) the robustness of the control for confounding factors (coastal effects, orography, synoptic forcing); (2) the length of the observational record (with longer records considered more reliable); (3) the spatial and temporal resolution of data; and (4) the appropriateness of the statistical approach. Studies with explicit control for confounding factors and longer observational records were weighted more heavily in synthesis conclusions.

IV. RESULTS AND DISCUSSION

4.1 Comparative Urban Convective Enhancement Across Tropical Megacities

Table I summarizes representative findings on urban-induced convective rainfall modification reported across the tropical megacity case studies reviewed in Section II.

TABLE 1
REPORTED URBAN CONVECTIVE/PRECIPITATION ENHANCEMENT ACROSS TROPICAL MEGACITIES

City	UHI intensity (daytime LST anomaly)	Rainfall frequency anomaly	Spatial pattern	Dominant mechanism inferred	Source
Mumbai	3–6°C	Significant increase, pre-monsoon short-duration cells	Over city and downwind (Konkan coast)	Thermal convergence	[9]
Jakarta	3–5°C	Enhanced afternoon convective frequency	Downwind, modulated by sea breeze	Thermal + sea-breeze interaction	[10]
Manila	2–5°C	Enhanced convective rainfall during southwest monsoon	Over city and downwind	Thermal + coastal interaction	[16]
São Paulo	3–7°C	Enhanced summer convective rainfall	Eastern/southern suburbs	Thermal + roughness	[16]
Coastal Chinese megacities	4–8°C	Variable: enhancement or suppression	Dependent on sea-breeze phase alignment	Thermal + mechanical	[11]
Houston (reference mid-latitude case)	2–5°C	Increased downwind rainfall (foundational study)	30–60 km downwind	Thermal + aerosol	[5]
Global TRMM composite (multi-city)	Variable	Consistent downwind enhancement, stronger in humid climates	Downwind, climate-dependent	Thermal (dominant), aerosol (secondary)	[6]
WRF-UCM sensitivity experiments (generic tropical domain)	Model-dependent	Reduced convective initiation frequency when urban land cover removed	Concentrated over urbanized grid cells	Thermal convergence (attributed)	[12]

4.2 Mechanistic Attribution Patterns

The comparative results in Table I indicate that the thermally driven convergence mechanism is the most consistently identified driver of urban convective enhancement across both observational and modeling studies, appearing as a contributing factor in every case reviewed [4], [9]–[12]. The aerosol invigoration pathway appears as a secondary but non-universal contributor, most clearly implicated in the foundational Houston studies where aerosol concentrations were exceptionally high due to industrial and vehicular emissions [5], [7], while its role in the tropical megacity case studies reviewed here is less definitively isolated due to the confounding presence of simultaneous thermal and mechanical forcing.

The relative importance of the three pathways varies systematically with city characteristics. In inland cities or cities with strong thermal contrasts, the thermal pathway dominates. In cities with high aerosol loading (such as Mumbai and other South Asian megacities with substantial industrial and vehicular emissions), the aerosol pathway likely contributes to convective invigoration, though isolating its effect from the thermal pathway remains challenging. In cities with extreme building density and height variability (such as São Paulo or Manhattan), the mechanical pathway may play a more significant role in triggering convection.

4.3 Role of Coastal Geometry and Sea-Breeze Interaction

A recurring and mechanistically important finding is that coastal tropical megacities exhibit a qualitatively different convective response than inland cities because the urban heat island circulation interacts, and can either constructively or destructively interfere, with the independently forced sea-breeze circulation [10], [11]. When the phase and orientation of these two circulations align, the resulting convergence zone is intensified and convective enhancement is amplified; when they are misaligned, urban rainfall enhancement can be reduced or displaced from what a purely thermal-convergence model would predict. This finding indicates that urban rainfall enhancement magnitude cannot be predicted from UHI intensity alone and must account for city-specific coastal geometry and diurnal sea-breeze timing.

For Jakarta, the sea-breeze from the Java Sea to the north interacts with the urban-induced circulation to create a complex convergence pattern that shifts position throughout the day. During the afternoon, when the sea breeze is strongest, the convergence zone can be displaced several kilometers inland, overlapping with the urban heat island circulation and producing intense localized convective initiation. In contrast, during the morning or evening, the two circulations may be misaligned, and convective enhancement is reduced.

For Mumbai, the western coastal location (adjacent to the Arabian Sea) means that the sea-breeze circulation is generally weaker than in Jakarta, and the urban-induced thermal circulation tends to dominate the convective response. However, during the monsoon season, the complex interaction between the monsoon flow, the sea breeze, and the urban heat island can produce highly variable rainfall patterns, with the urban signature sometimes obscured by the large-scale monsoon dynamics.

For Manila, the complex coastal geometry—with Manila Bay to the west and Lake Laguna to the south—creates multiple sea-breeze circulations that can interact with the urban heat island in complex ways. Studies have shown that the convergence between the urban heat island circulation and the lake breeze can produce particularly intense convective initiation during the southwest monsoon season.

4.4 Temporal Dynamics and Diurnal Patterns

The diurnal evolution of UHI-convection coupling is an important dimension that the literature increasingly addresses. While the UHI effect typically peaks at night, the convective response is most pronounced during the afternoon, when solar heating maximizes both surface temperatures and atmospheric instability. There is typically a lag of several hours between the peak UHI intensity (often in the late afternoon or early evening) and the peak convective response (which may occur several hours after the thermal peak). This lag reflects the time required for the urban thermal perturbation to generate the mesoscale circulation and for parcels to ascend to the level of free convection.

Seasonal variations in UHI-convection coupling are also significant. In monsoon climates (Mumbai, Manila), the effect is most pronounced during the pre-monsoon and monsoon-onset periods, when the background atmosphere is highly unstable but convective initiation is not yet suppressed by widespread cloud cover. In equatorial climates (Jakarta, Singapore), the effect may be more consistent throughout the year, as the background conditions are more uniformly unstable. In subtropical climates (São Paulo), the effect is most pronounced during the summer months (November to March), when convective instability is highest.

4.5 Modeling Uncertainty and Attribution Confidence

The WRF-UCM sensitivity experiments reviewed provide the strongest available process-level attribution evidence, since they isolate the causal effect of land-use change under controlled boundary conditions [12]. However, the substantial sensitivity of these results to urban canopy parameterization scheme and model resolution introduces meaningful uncertainty into quantitative enhancement estimates, with coarser-resolution simulations tending to smear out and underestimate the spatial concentration of urban-triggered convection relative to higher-resolution configurations [13]. This suggests that attribution confidence should be weighted toward studies employing convection-permitting resolution (horizontal grid spacing below approximately 3 km) and multi-layer urban canopy schemes that explicitly resolve building-height-dependent heat storage and roughness effects.

Furthermore, the representation of anthropogenic heat flux—the heat released from vehicles, buildings, and industrial activity—introduces substantial uncertainty. Anthropogenic heat flux can contribute significantly to the urban energy balance, particularly in dense urban areas, but its magnitude and spatial distribution are difficult to quantify with confidence. As a result, modeling studies that include realistic anthropogenic heat fluxes generally simulate stronger urban-convection coupling than those that neglect this forcing. Future work should focus on improving the specification of anthropogenic heat flux through better emission inventories and land-use classification schemes.

4.6 Urban Morphology and Configuration Effects

The influence of urban morphology on convective response deserves separate attention. Studies that have explicitly examined the role of building geometry find that cities with high building density and height variability generate stronger mechanical convergence and more frequent convective initiation than cities with more uniform building heights. Similarly, cities with significant green space fraction—parks, gardens, and green roofs—exhibit reduced UHI intensity and correspondingly lower convective enhancement. These findings suggest that urban form—not just urban extent—is a critical determinant of UHI-convection coupling.

The comparison between compact (high-density) versus sprawling (low-density) urbanization patterns is particularly relevant. Compact cities, with high building density and limited green space, generally exhibit stronger UHI intensity and more pronounced convective enhancement than sprawling cities. However, the spatial pattern differs: compact cities tend to produce more concentrated convective initiation over the urban core, while sprawling cities may produce more diffuse enhancement over a broader downwind area. These differences have implications for flood-risk management, as concentrated enhancement over the urban core exacerbates the risk of urban flash flooding.

4.7 Flood-Risk Implications

The convective enhancement documented here does not occur in isolation but compounds directly with the hydrological consequences of urbanization. Because the same impervious surface expansion that drives UHI intensification also reduces infiltration capacity, the UHI-enhanced convective rainfall occurs over surfaces that are already less able to absorb it [14]. This compounding effect—simultaneously increasing the rainfall forcing and reducing the capacity to absorb that forcing—means that UHI-convection feedback should be treated as a joint hydrometeorological hazard rather than an atmospheric phenomenon considered separately from urban flood risk.

The implications are particularly severe for tropical megacities because: (1) the convective enhancement is most pronounced during high-intensity, short-duration events that are most likely to cause flash flooding; (2) the background tropical rainfall climatology is already characterized by high-intensity events; (3) rapid urbanization has dramatically increased impervious surface cover; and (4) many tropical megacities have inadequate drainage infrastructure. This combination of factors means that UHI-convection enhancement can substantially exacerbate already severe flood risks in tropical megacities.

Integration of atmospheric and hydrological models is essential for quantitative flood-risk assessment. Coupled WRF-UCM—hydrological models can simulate the full cascade from urbanization to convective enhancement to surface runoff, providing a more complete picture of flood risk. However, such integrated modeling frameworks are still relatively rare in the literature, and methodological challenges remain in coupling models that operate at very different spatial and temporal scales.

4.8 Summary of Key Findings

Collectively, the reviewed evidence supports a coherent, physically grounded picture in which tropical megacity urbanization enhances convective storm initiation primarily through thermally driven mesoscale convergence, with aerosol and mechanical pathways contributing secondary, city-specific modulation. The consistency of the downwind displacement pattern across geographically and climatically diverse cities, from Houston to Mumbai to Jakarta, strengthens confidence that this is a genuine physical effect of urbanization rather than an artifact of any single observational or modeling methodology [5], [6], [9], [10]. At the same time, the pronounced sensitivity of both observed and simulated enhancement magnitude to coastal geometry, background aerosol loading, and model resolution indicates that no single universal enhancement factor can be applied across all tropical megacities; city-specific assessment remains necessary for operational risk applications.

V. CHALLENGES IN UNDERSTANDING UHI-CONVECTION FEEDBACK

Several challenges limit further progress in this field and should be acknowledged explicitly.

5.1 Mechanistic Disentanglement

Mechanistic disentanglement remains difficult because thermal, aerosol, and mechanical pathways operate simultaneously in real cities, making it challenging to isolate their individual contributions using observational data alone, since controlled removal of any single pathway is only achievable in idealized model sensitivity experiments [7], [8], [12]. The lack of controlled experimental manipulation in observational studies means that attribution is inherently correlational rather than causal. Furthermore, the interactions between pathways—for example, the influence of aerosols on the thermal pathway through their effect on radiative forcing—add additional complexity.

5.2 Urban Canopy Parameterization Uncertainty

Urban canopy parameterization uncertainty continues to introduce substantial spread in simulated enhancement magnitude, particularly regarding anthropogenic heat flux specification and building-height-dependent roughness representation [13]. The various urban canopy models available—from simple slab models to sophisticated multi-layer schemes—produce different surface energy fluxes and boundary-layer responses, leading to different convective responses. There is no consensus on which scheme is "best" for tropical megacity applications, and model intercomparison studies are needed to quantify the spread of uncertainty.

5.3 Aerosol-Convection Interaction

Aerosol-convection interaction remains scientifically contested, with reported effects ranging from invigoration to suppression depending on background conditions, limiting confident generalization of the aerosol pathway's net contribution across cities [7], [15]. The non-monotonic nature of the aerosol effect means that the direction of the influence—whether urban aerosol emissions enhance or suppress convection—depends on background aerosol concentration, humidity, and wind shear, among other factors. This makes it difficult to generalize across cities with different aerosol backgrounds.

5.4 Coastal and Sea-Breeze Interaction Complexity

Coastal and sea-breeze interaction complexity adds a further layer of city-specific variability that complicates cross-city generalization of enhancement magnitude and spatial pattern [10], [11]. The diurnal and seasonal timing of the sea breeze, relative to the UHI circulation, determines whether the two circulations constructively or destructively interfere. This means that cities with similar UHI intensities can have very different convective responses if their sea-breeze characteristics differ.

5.5 Compounding Flood-Risk Quantification

Compounding flood-risk quantification remains underdeveloped, as most convective-enhancement studies do not explicitly couple their findings to urban drainage capacity or infiltration modeling, leaving a gap between atmospheric science findings and practical urban flood-risk assessment [14]. The hydrological consequences of UHI-enhanced convective rainfall—how much additional runoff is generated—have not been systematically quantified, limiting the use of these findings in flood-risk management.

5.6 Temporal Data Limitations

The temporal length and consistency of observational records present additional challenges. Many urban rainfall enhancement studies rely on relatively short satellite records (e.g., TRMM, which operated from 1997 to 2015) or rain-gauge networks with varying densities and changing station locations over time. Longer and more consistent observational records are needed to establish robust statistical signatures and to detect trends in urban-convection coupling as cities continue to expand.

5.7 Climate Change Interactions

The influence of climate change on UHI-convection feedback is a major and relatively unexplored challenge. Rising background temperatures will increase atmospheric moisture content and convective instability, potentially amplifying the urban-convection coupling. At the same time, changes in large-scale circulation patterns may alter the background synoptic forcing, either amplifying or dampening the urban enhancement. Future work should explicitly incorporate climate change scenarios into UHI-convection studies to understand how the feedback may evolve over the coming decades.

VI. CONCLUSION

This study has reviewed the physical mechanisms and empirical evidence linking urban heat island intensification to convective storm initiation in tropical megacities. Thermally driven urban convergence emerges as the most consistently supported mechanism across observational, satellite, and coupled modeling studies, producing a characteristic downwind or over-city enhancement of convective rainfall frequency and intensity [4]–[6], [9]–[12]. Aerosol-mediated microphysical modification and surface-roughness-induced mechanical convergence contribute secondary, city-specific modulation whose relative importance depends on local aerosol loading, building morphology, and coastal geometry [7], [8], [10], [11]. Reported enhancement magnitudes vary considerably across the tropical megacities reviewed—Mumbai, Jakarta, Manila, São Paulo, coastal Chinese cities, and the foundational Houston case—underscoring that urban-convection feedback cannot be characterized by a single universal relationship but requires city-specific assessment informed by local climatology and urban form [9]–[11].

The review has also identified several critical uncertainties: mechanistic disentanglement remains difficult because thermal, aerosol, and mechanical pathways operate simultaneously; urban canopy parameterization choices introduce substantial spread in simulated enhancement; aerosol-convection interaction remains contested; coastal and sea-breeze effects add city-specific variability; and compounding flood-risk quantification remains underdeveloped. The temporal evolution of UHI-convection coupling under continued urbanization and climate change represents a major future research priority.

Because this convective enhancement occurs over increasingly impervious urban surfaces with reduced infiltration capacity, UHI-convection feedback represents a compounding hydrometeorological hazard with direct implications for urban flood risk management, warranting integration of atmospheric science findings into urban planning and drainage infrastructure design [14]. Urban planners should not treat UHI and flood risk as separate phenomena but should recognize that they are connected through the land-atmosphere feedbacks described in this review. Enhanced convective rainfall over impervious surfaces increases runoff generation and flood risk, meaning that efforts to mitigate UHI—such as increasing green space—can simultaneously reduce flood risk through improved infiltration.

VII. FUTURE WORK

Future research should prioritize the following areas:

7.1 High-Resolution Modeling

High-resolution, convection-permitting coupled urban-canopy simulations should be conducted across a broader and more climatically diverse sample of tropical megacities to improve cross-city generalization of enhancement magnitude and mechanistic attribution. These simulations should employ horizontal grid spacings below 3 km to resolve convective processes explicitly and should include multi-layer urban canopy schemes that represent building-height heterogeneity and anthropogenic heat fluxes realistically.

7.2 Mechanistic Disentanglement

Further work is needed to disentangle the relative contributions of thermal, aerosol, and mechanical pathways within a single observational framework, potentially through combined radar, aerosol lidar, and boundary-layer profiler deployments during targeted field campaigns. Such campaigns should be designed to measure the three pathways simultaneously, allowing for statistical attribution of their relative contributions.

7.3 Urban Canopy Parameterization Refinement

Continued refinement of urban canopy parameterizations, particularly multi-layer schemes resolving building-height heterogeneity and anthropogenic heat flux variability, should be pursued to reduce model-attribution uncertainty. Model intercomparison studies are needed to quantify the spread of uncertainty across different schemes and to identify the most appropriate schemes for tropical megacity applications.

7.4 Flood-Risk Integration

Research should explicitly couple urban-convection enhancement findings with urban hydrological and drainage capacity modeling to quantify compounding flash-flood risk under continued urbanization and climate warming scenarios. This integration should be operationalized through coupled atmospheric-hydrological modeling frameworks that can simulate the full cascade from urbanization to convective enhancement to surface runoff.

7.5 Climate Change Interactions

Studies should examine how projected future urban expansion patterns in rapidly growing tropical megacities may further intensify UHI-convection feedback under climate change, providing forward-looking guidance for climate-resilient urban planning. These studies should incorporate climate change scenarios from the latest IPCC assessments and should consider both the effects of urban expansion and the effects of changing background climate.

7.6 Urban Morphology Studies

The influence of urban morphology—building height variability, green space fraction, street canyon geometry—on UHI-convection coupling should be systematically examined to provide design guidance for climate-resilient urban development. Studies should compare different urban forms (compact vs. sprawling) and their effects on convective response.

7.7 Observational Programs

Long-term observational programs should be established in representative tropical megacities to build consistent, multi-decadal records of UHI intensity, convection, and rainfall. These records are essential for detecting trends, validating models, and understanding the temporal evolution of UHI-convection coupling.

7.8 Policy Implications

Research should engage with urban planning and policy communities to translate findings into actionable guidance. This includes developing practical metrics for assessing urban-convection enhancement and flood risk in planning contexts, and identifying effective mitigation strategies (e.g., green infrastructure, building codes, drainage design) that address both UHI and flood risk.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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