



Disentangling climate change and urbanization effects on future tropical cyclone compound flood hazards[☆]

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ABSTRACT

Tropical cyclone-induced compound flooding poses a growing challenge for low-lying coastal megacities, as climate change and continued urban development may further intensify these hazards. Yet most planning frameworks and hazard assessments remain anchored in historical extremes, failing to account for how future conditions may fundamentally reshape disaster potential. Here, we examine how the impacts of Super Typhoon Mangkhut (2018)—one of the most intense storms to strike the Greater Bay Area (GBA)—could change under future climate and urbanization conditions projected for SSP5–8.5, using a Pseudo-Global Warming (PGW) framework with high-resolution atmospheric and storm surge models linked through one-way forcing. Our results show that future warming substantially delays typhoon weakening during the critical landfall period, sustaining central pressure ~5 hPa lower and increasing rainfall intensity within 200 km of the typhoon center by ~27%, with a ~12% rise in storm surge. In contrast, projected future urbanization, with a transition towards taller and more compact urban forms, has a much smaller and more model-dependent additional effect on rainfall and storm surge (~1%). The integrated Compound Hazard Index (CHI) increases by ~19% on average under climate change alone and by ~21% when urbanization is included, further demonstrating the dominant role of climate change in the projected increase in compound hazard. By providing a case-study assessment of compound flood hazards associated with an extreme typhoon under a high-emissions future climate scenario, this study offers actionable insights for redesigning urban resilience strategies in a warming and urbanizing world.

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1. Introduction

Coastal cities are increasingly on the frontlines of climate change, where rising temperatures and expanding urban footprints converge to amplify the impacts of extreme weather. Among the most destructive of these are compound flood hazards—events that involve the simultaneous intensification of extreme rainfall and storm surge during tropical cyclones (TCs) (Nicholls et al., 2021; Buonomo et al., 2024; Grimley et al., 2024). These multi-hazard events threaten to overwhelm existing urban drainage, protection infrastructure, and emergency response systems, especially in densely populated low-elevation regions.

Rising sea surface temperatures and stronger ocean–atmosphere exchanges have altered atmospheric circulation and tropical cyclone behavior, making storms more likely to stall, intensify near the coast, and make landfall at peak strength—thereby increasing storm surges and localized rainfall (Kossin et al., 2020; Wang and Toumi, 2021; Wang et al., 2024). At the same time, rapid urbanization has fundamentally changed land surface properties, disrupting energy and water cycles (Yang et al., 2018; Bhattacharjee et al., 2022) and modifying the intensity, duration, and spatial pattern of extreme rainfall through enhanced land–atmosphere interactions (Zscheischler et al., 2018; Zhang et al., 2018). Much research has explored how a warming atmosphere and ocean fuel stronger TCs and how urbanization alters local hydrometeorological patterns, yet their combined impact on flooding remains poorly understood. Current hazard assessments and planning standards, often based on historical baselines (e.g., “1-in-100-year” rainfall), fail to capture how physical thresholds might be breached under future climate and land-use regimes.

Quantifying future TC-induced flood risk remains highly challenging due to multiple interrelated limitations. The low resolution of the reanalysis datasets and global climate models (GCMs) can lead to an underestimation of TC intensity and an inadequate representation of their fine-scale structures. Furthermore, the low frequency of extreme events and the scarcity of historical observational records limit the potential for statistical analysis due to insufficient sample sizes. These constraints are further compounded by the complex interactions among atmospheric warming, storm dynamics, and land surface modifications such as urbanization (Yin et al., 2015; Islam et al., 2023). Together, these challenges have led to a lack of consensus in projecting TC characteristics under climate change scenarios, especially at regional scales (Marsooli et al., 2019; Bloemendaal et al., 2022). Recent studies have shown that urbanization can enhance and redistribute TC-induced rainfall through changes in surface roughness and local atmospheric dynamics (Hu et al., 2023; Deng et al., 2025). Critically, despite growing research on the combined effects of climate change and urbanization on TC rainfall, their relative contributions to rainfall–storm surge compound hazards remain poorly quantified (Green et al., 2025), particularly in highly vulnerable urban estuaries like the Guangdong–Hong Kong–Macao Greater Bay Area (GBA), one of the world's largest and most densely populated urban agglomerations, encompassing 11 cities including Hong Kong, Macau, Guangzhou and Shenzhen (Fig. 2).

To address these gaps, this study applies a Pseudo-Global Warming (PGW) approach to dynamically simulate the future evolution of Super Typhoon Mangkhut (2018) under the high emission Shared Socioeconomic Pathway 5–8.5 (SSP5–8.5) climate projections and anticipated urbanization. It was a historically extreme event that brought intense rainfall (420 mm), peak gusts (62.8 m/s), and storm surges up to 323 cm, causing widespread flooding and damage in the region (Guangdong Meteorological Bureau, 2023). The simulation focuses on the typhoon's landfall and decay phase, when compound flood impacts are most acute. We use a high-resolution modelling system (WRF for atmospheric processes and PMOST for storm surge), incorporating projected land-use change and climate-driven thermodynamic shifts. A novel Compound Hazard Index (CHI) is developed to quantify the joint evolution of rainfall and storm surge hazards. This study is organized around three key questions: (1) How does urbanization affect TC-induced rainfall and storm surge? (2) How does climate change influence the hazard dynamics of a landfalling typhoon? (3) How do compound flood hazards change when climate change and urbanization are considered together? By exploring the high-end potential of compound flood hazards under future climate and urban conditions, this research provides forward-looking insights to support the design of more robust flood protection, early warning systems, and land-use planning for severe future flood conditions.

2. Methods

2.1. Scenario design and modelling framework

In line with the research objectives, this study adopts a scenario-based storyline approach to quantify the effects of urbanization and climate change on TC-induced flooding. Five distinct scenarios, summarized in Table 1, are designed to distinguish the effects of urbanization and climate change and assess their combined influence. The LU-1980 scenario is included solely as a supporting case to illustrate the substantial urban expansion that occurred between 1980 and 2020, thereby providing clearer contrast for assessing the

Table 1
Scenario Definitions.

Experiment	Name of Scenario	Description
Control experiment	Control Scenario (LU-2020)	Current Climate + Land use in 2020
	Future Urbanization-Only Scenario (LU-2100)	Current Climate + Land use in 2100
Sensitivity experiment	Future Climate-Only Scenario (CLIM-2100)	Future climate + Land use in 2020
	Combined Future Scenario (COMB-2100)	Future climate + Land use in 2100
Supporting experiment (for supporting comparison only)	Historical Urbanization Scenario (LU-1980)	Current climate + Land use in 1980

marginal effects of future urbanization. It is not involved in the future scenario analysis. Each scenario is implemented through both the Weather Research and Forecasting (WRF) and Parallel Model of Storm Surge from Typhoon (PMOST) models, enabling a consistent assessment of compound flooding drivers—rainfall and storm surge. To further quantify the combined changes in rainfall and storm surge hazards, we define a Compound Hazard Index (CHI) based on both hydrometeorological components. Specifically, CHI is computed as the geometric mean of standardized rainfall and storm surge anomalies:

$$CHI = \sqrt{R^* \times S^*}$$

where R^* and S^* denote the normalized deviations of precipitation and storm surge, respectively, relative to the control scenario. The overall framework is illustrated in Fig. 1.

2.2. Land use scenarios

To reconstruct the 1980 land use scenario, this study referred to the 1-km resolution land-use dataset in China (Chinese Academy of Sciences Resource and Environmental Science Data Center, 2019) and adjusted the CGLC-MODIS-LCZ data to represent historical land use distributions (Fig. 2a). Additionally, based on the work of Chen et al. (2021), this study utilized the 100-m resolution LCZ map of the GBA for 2020 ($\kappa = 0.876$) and their projected land use for 2100 under the SSP5–8.5 scenario, which incorporates socioeconomic factors such as GDP, population, and urbanization rates. These data were used to modify the CGLC-MODIS-LCZ dataset, with adjustments to reflect land use distributions for 2020 and 2100 (Fig. 2b & c).

The analysis of these reconstructions highlights significant shifts in land use patterns over time. In 1980, aside from the dense urban regions of Hong Kong and Macau, the rest of the GBA largely remained in the early stages of urbanization, with relatively few urbanized areas. By 2020, however, after 40 years of rapid urban expansion, the land use had undergone significant transformations, with a dramatic increase in urbanized areas. In contrast, the projected changes from 2020 to 2100 are much more limited, particularly in terms of horizontal urban expansion. This limited change is attributed primarily to SSP scenario projections, which predict a population decline in China after the 2050s, leading to stagnation in the demand for urban land (Chen et al., 2021). Under this future development pattern, urban growth shifts from large-scale outward expansion towards denser and taller development within existing urban areas. Quantitatively, the newly urbanized area in LU-2100 corresponds to approximately 14% of the built-up area in LU-2020. High-rise and mid-rise LCZ classes increase by 22.5% and 21.7%, respectively, compared with an 8.9% increase in low-rise classes, while compact urban classes increase by 24.1%, substantially more than open urban classes (11.5%). Previous modelling work for Typhoon Lekima over the Shanghai metropolitan area has shown that building height can influence surface roughness and local dynamical processes, with implications for the simulation and spatial distribution of TC-induced rainfall (Ao et al., 2022). Although that study focused on a different coastal megacity and TC event, it provides relevant evidence that changes in urban morphology may influence TC rainfall in highly urbanized coastal environments. Notably, the projected land use for 2100 used in this study does not include the ecological control line and therefore represents the maximum potential for urban development under this scenario.

2.3. Climate change scenarios

This study employs the Pseudo-Global Warming (PGW) method to simulate the landfall and decay phase of Typhoon Mangkhut after it reaches peak intensity, rather than its entire lifecycle. This approach reduces uncertainties associated with future track projections. This phase is typically accompanied by intense rainfall and storm surges—key hazard components that are strongly affected by the joint effects of future climate change and urbanization. Climate change differences (Δ) were calculated as the difference in monthly averages between the far future (2071–2100) and the current period (1985–2014) under the SSP5–8.5 scenario, including variables such as relative humidity, surface pressure, sea level pressure, air temperature, surface temperature, geopotential height, wind speed (U, V), soil temperature, and soil moisture content. Six GCMs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were selected based on coverage of the 10 necessary variables and relatively high resolution (≤ 100 km for atmospheric and

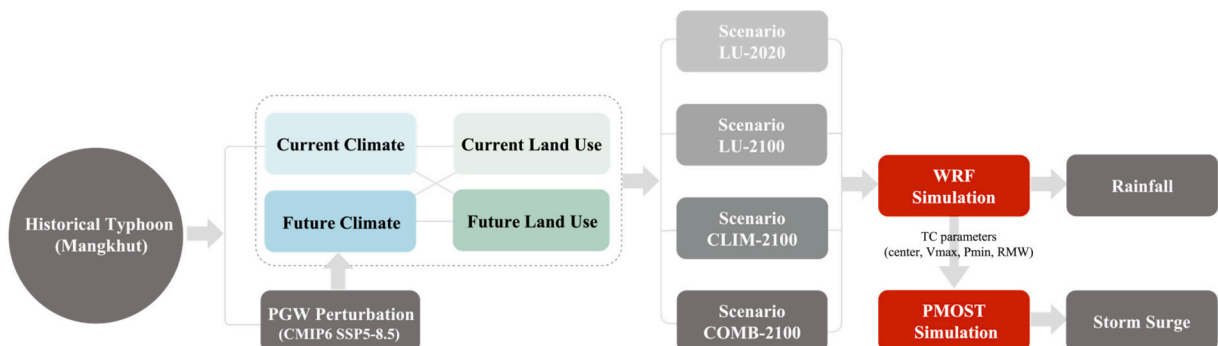


Fig. 1. Schematic diagram of the modelling framework.

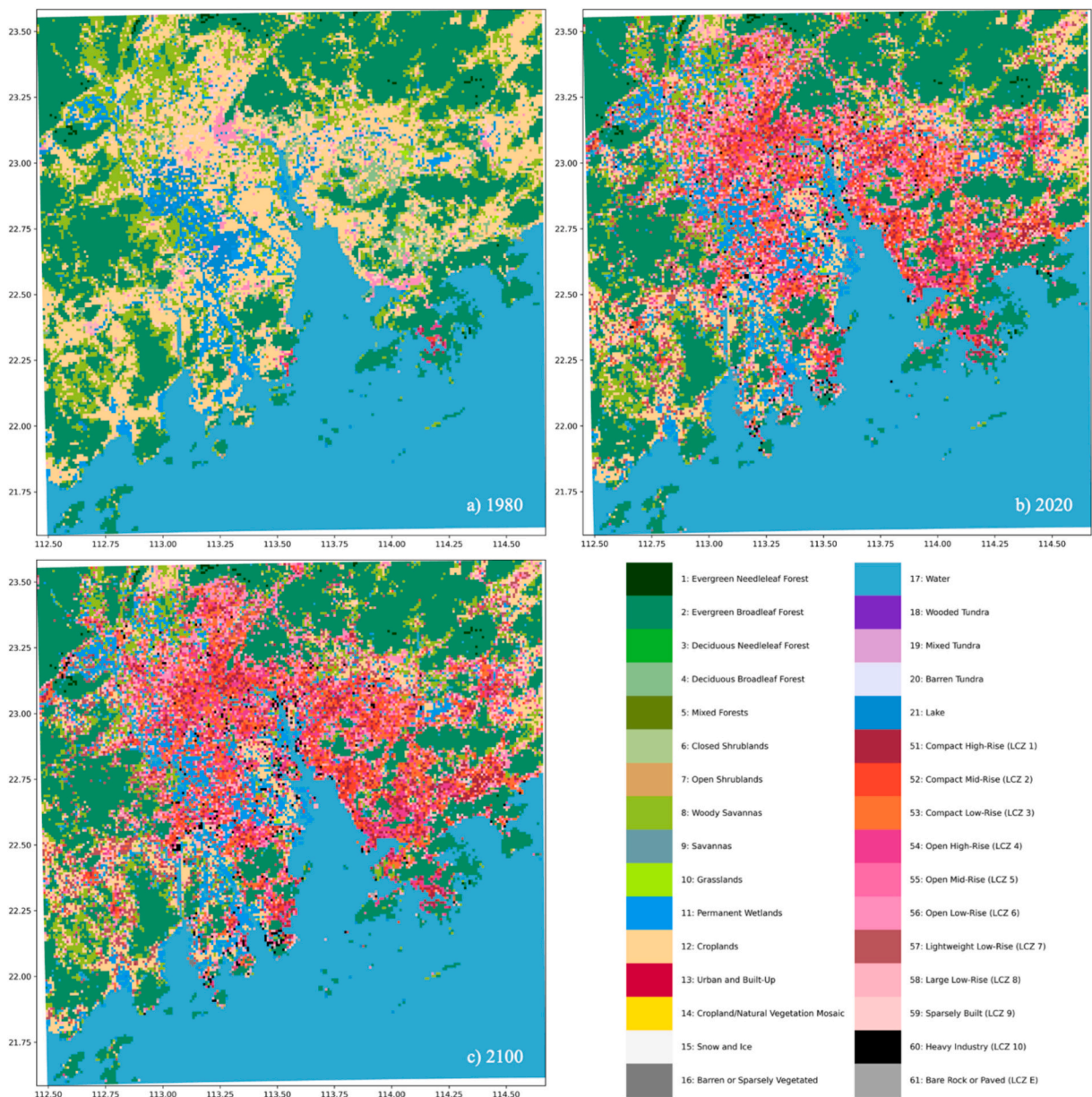


Fig. 2. Map of land use in a)1980, b)2020 and c) 2100.

oceanic grids): BCC-CSM2-MR, CAS-ESM2-0, CMCC-CM2-SR5, EC-Earth3P-HR, MPI-ESM1-2-HR, and NorESM2-MM. Model details are provided in Table S2.

A linear interpolation was applied to map the 19-layer climate change atmospheric differences and the multi-layer soil deltas onto WRF's 32 vertical atmospheric layers and four soil layers, respectively (Fig. 3). This approach ensures consistency between the models' vertical structures while maintaining the accuracy of the PGW approach. For soil moisture, as GCMs provide variable MRSO (kg/m^2) for the 0–100 cm depth (Sravani et al., 2022), it is converted into WRF's soil moisture fractions by distributing the total moisture across WRF's layers (0–10 cm, 10–40 cm, 40–100 cm) using either a uniform or depth-based approach. No change was assumed for the 1–2-m layer due to the lack of data and minimal expected moisture variation (Berg et al., 2017), ensuring compatibility with WRF's fractional soil moisture representation.

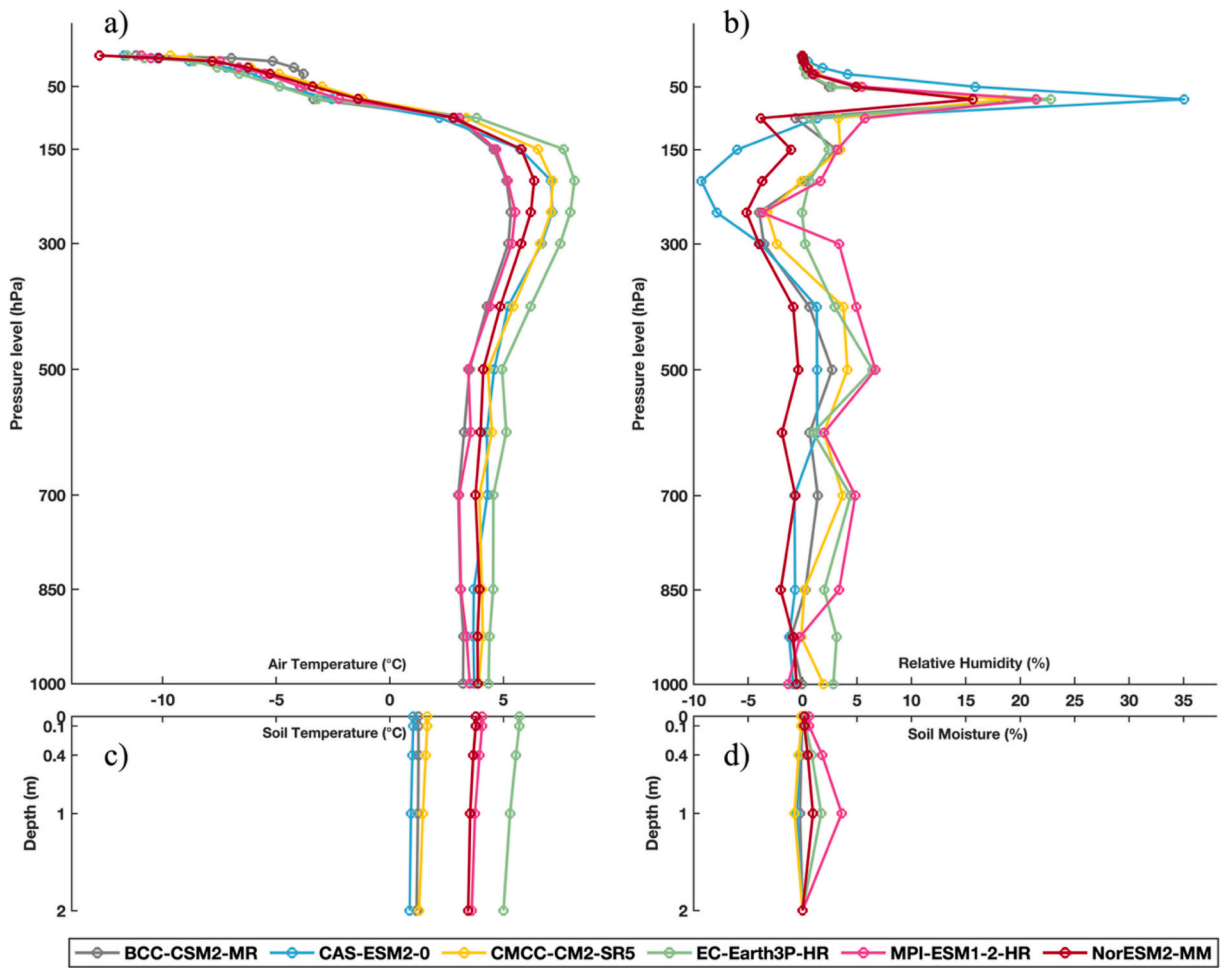


Fig. 3. Vertical profiles of September D01-averaged a) Δ temperature, b) Δ relative humidity, c) Δ soil temperature and d) Δ soil humidity.

2.4. Models

2.4.1. Atmospheric model

The WRF model version 4.5 coupled with the Noah land-surface model (LSM) is employed to simulate Typhoon Mangkhut. Two-way nesting is used with horizontal grid resolutions of 9, 3, and 1 km, respectively (Fig. 4a). The simulation starts at 0600 UTC 15 September and ends at 1800 UTC 17 September 2018. The typhoon made landfall at 0900 UTC on 16 September. The first nine hours of the model simulation are considered a spin-up period and have been excluded from the analysis (Kain et al., 2010; He et al., 2023). The study focuses on the period from 18 h prior to landfall to 24 h post-landfall, specifically from 1500 UTC on 15 September to 0900 UTC on 17 September 2018. To better represent urban physical processes and improve the accuracy of the results, both the hybrid global 100-m CGLC-MODIS-LCZ land cover dataset (Demuzere et al., 2023) and the Urban Canopy Model (UCM) are employed. In the WRF model, urban canopy parameterization is handled by the multi-layer canopy scheme (Building Effect Parameterization, BEP). The specific urban parameter settings follow the configurations developed by Xin et al. (2023).

The parameterization schemes used in this study include the Kain-Fritsch cumulus scheme (Kain, 2004), applied only to Domain 1 (D1), and deactivated in D2 and D3; the Rapid Radiative Transfer Model (RRTM) schemes (Mlawer et al., 1997; Iacono et al., 2008) for shortwave and longwave radiation; the Yonsei University planetary boundary layer (PBL) scheme (Hong and Pan, 1996; Hong et al., 2006); and the Double-Moment 5-Class (WDM5) mixed-phase microphysics scheme (Lim and Hong, 2010). The basis for selecting these configurations is provided in the Supplementary Method. The accumulated rainfall from 18 h before to 24 h after landfall in the control scenario is compared with observations from CLDAS-V2.0 in Fig. 5a and b. The comparison shows a spatial correlation coefficient of 0.38 and a root mean square error (RMSE) of 73.0 mm. The simulated rainfall is generally higher than the observed values, with relatively large discrepancies particularly over mountainous areas. This overestimation may result from biases in the initial meteorological and boundary conditions, limitations in the physical parameterization schemes, as well as deviations in the simulated

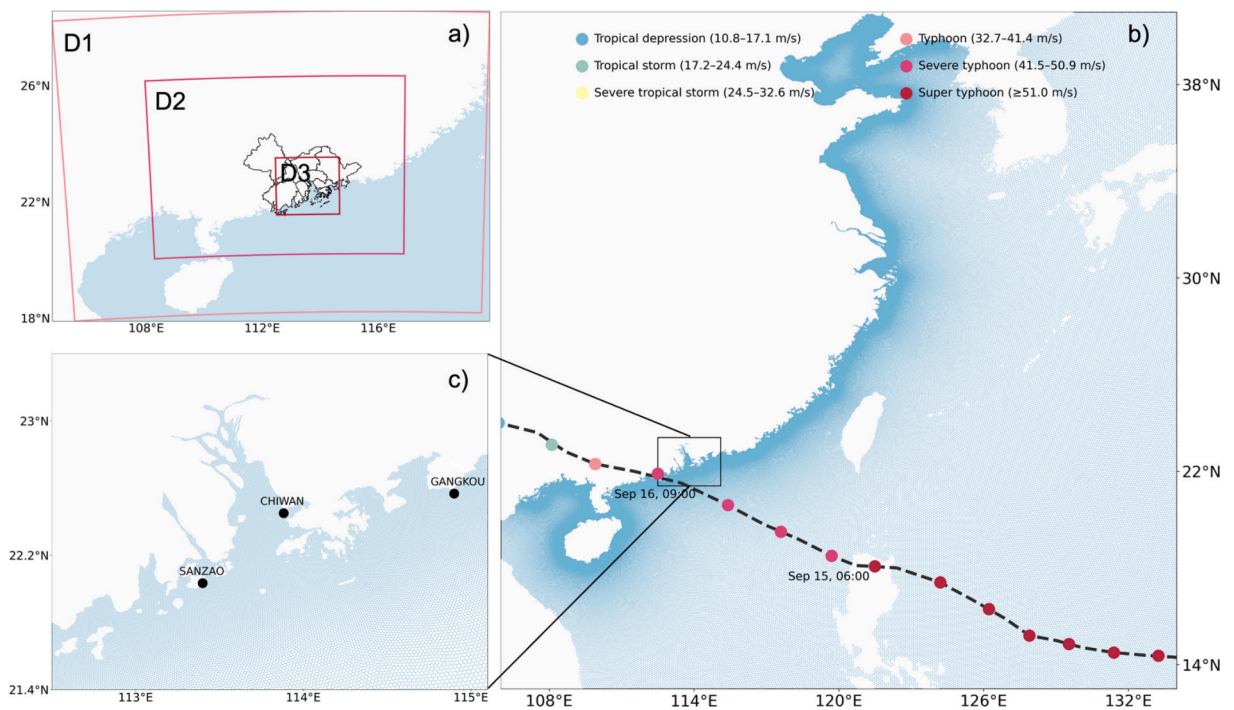


Fig. 4. a) WRF model domain configuration with three nested domains, the black polygon indicates the GBA region. b) Unstructured hexagonal grid mesh for the PMOST model, along with the track of Typhoon Mangkhut derived from the CMA Tropical Cyclone Best Track Dataset. c) Locations of the three tide gauge stations used in this study.

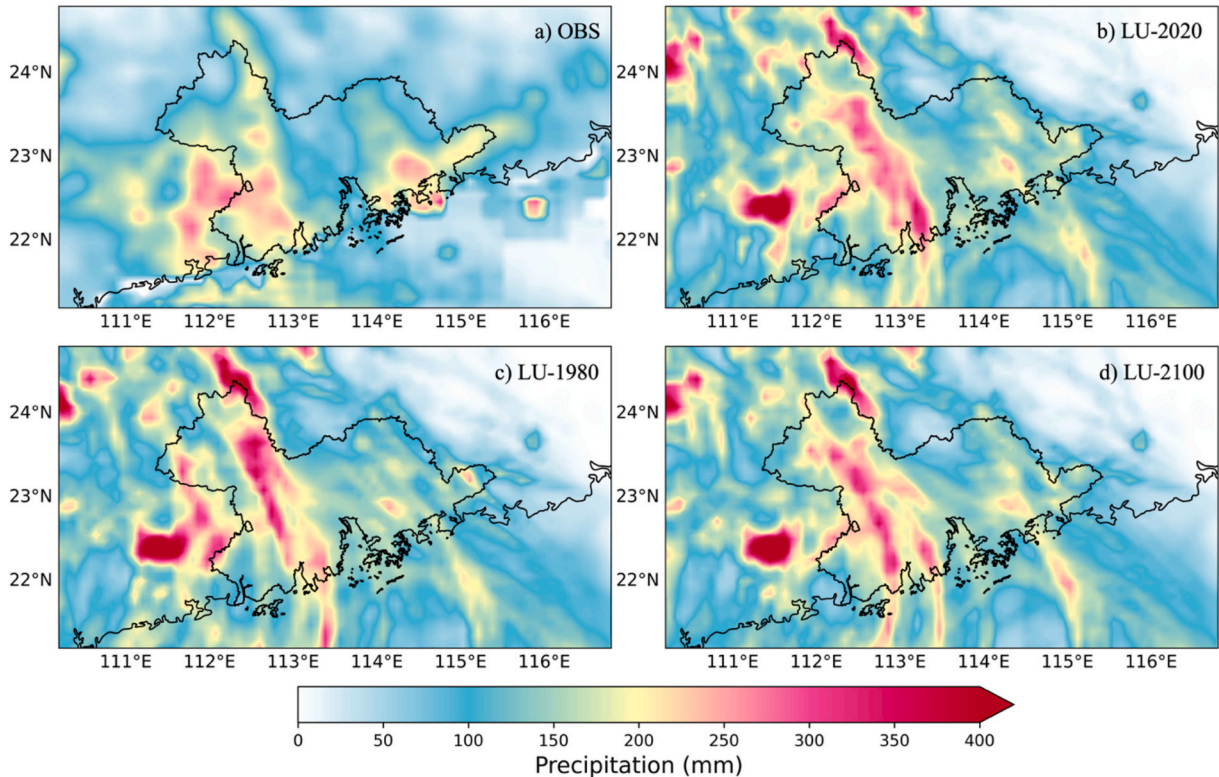


Fig. 5. Accumulated rainfall from a) observations, b) LU-2020, c) LU-1980 and d) LU-2100.

track after landfall (He et al., 2023). Accurately reproducing TC-induced extreme rainfall remains challenging in WRF simulations, particularly for strongly convective and spatially heterogeneous rainfall events (Tian et al., 2021). Despite these discrepancies, the simulation captures the broad spatial characteristics of the observed rainfall associated with Typhoon Mangkhut.

2.4.2. Storm surge model

PMOST, developed by the National Marine Environmental Forecasting Center of China, is employed to simulate storm surges. PMOST is driven by atmospheric forcing (one-way) derived from key typhoon parameters diagnosed from the WRF simulations, including storm center location, minimum central pressure, 10-m maximum wind speed, and Radius of Maximum 10-m Tangential Wind Speed (RMW). PMOST utilizes an unstructured hexagonal grid based on the Spherical Centroidal Voronoi Tessellation (SCVT) technique, allowing for flexible grid refinement, with resolutions ranging from 50 km in the open ocean to 2 km near the coast (Fig. 4b). PMOST was validated against observed hourly storm surges at three tide gauge stations (SANZHAO, CHIWAN, and GANGKOU). The RMSEs ranged from 0.28 to 0.86 m across the three stations, while the timing of the observed surge peaks was captured within 2 h. Despite some discrepancies in surge magnitude, the simulations reasonably reproduced the overall temporal evolution of the storm surge, supporting the suitability of the modelling framework for the scenario-based analysis conducted in this study. Detailed validation results are provided in the Supplementary Method (Fig. S4).

3. Results

3.1. Impacts of urbanization on rainfall and storm surge (LU-1980 → LU-2020 → LU-2100)

To assess the impact of urbanization on TC-induced flood hazards, three land use scenarios representing different stages of urban development—LU-1980, LU-2020, and LU-2100—were compared under identical atmospheric forcing conditions. The LU-1980 simulation is included as a supporting scenario to illustrate the substantial urban expansion that occurred between 1980 and 2020, thereby providing a clearer contrast for evaluating the marginal effects of future urbanization. This setup enables an assessment of both the cumulative and incremental effects of urbanization on TC-related rainfall and storm surge.

3.1.1. Rainfall

Although the cumulative rainfall shows no substantial differences across the three urbanization scenarios (Fig. 5), the LU-1980 simulation reveals a coastal-to-inland enhancement pattern. With the increase urbanization of LU-2020 and LU-2100 scenarios, the pattern shifts with rainfall intensifying along the coast, where simulations show a sharp rise in coastal rainfall, followed by a decrease further inland. This spatial redistribution of rainfall is more clearly illustrated by the rainfall hotspot distributions shown in Supplementary Fig. S5. Such concentrated coastal rainfall may elevate the risk of flooding in these areas.

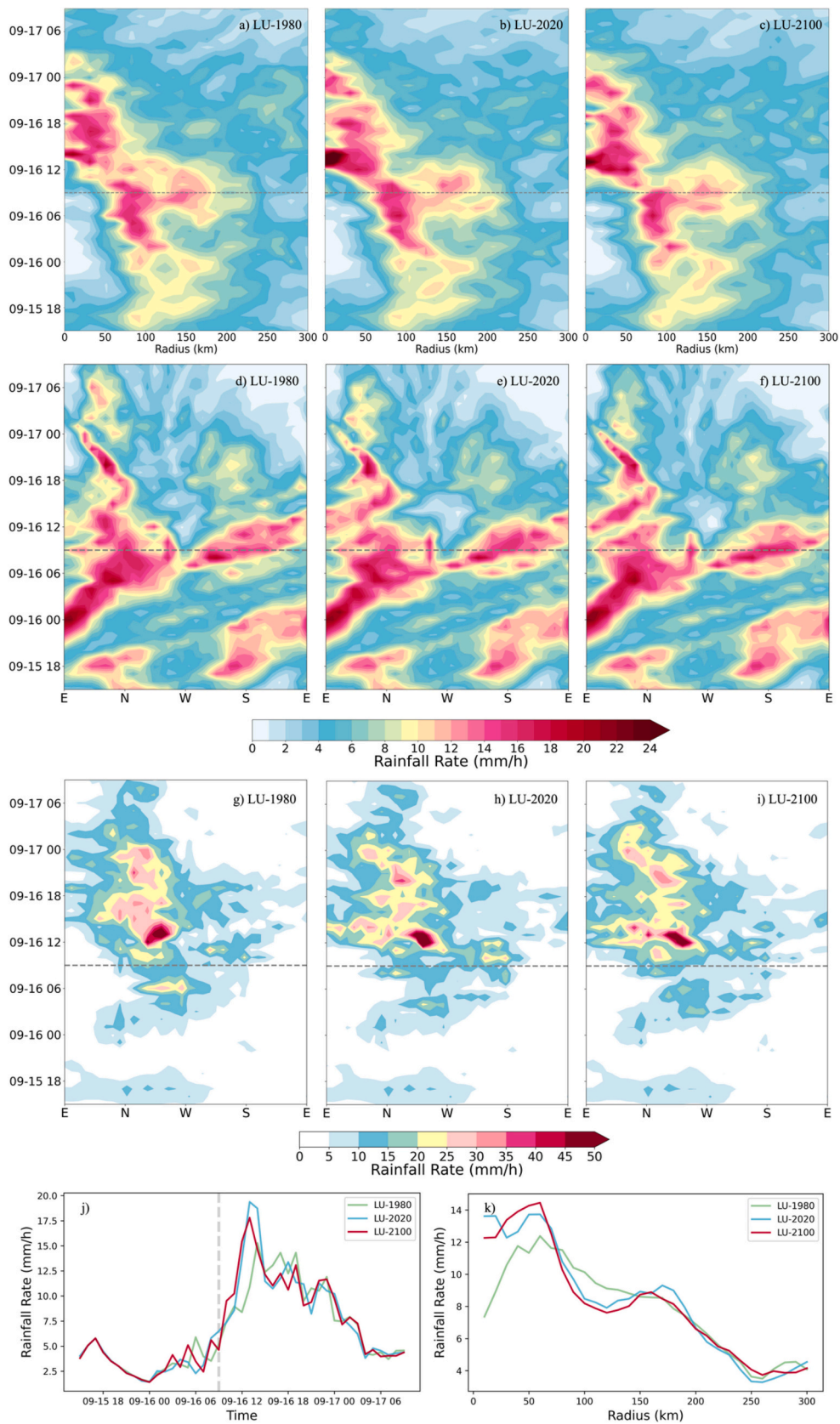
Fig. 6a-c present the time-radius Hovmöller diagrams of azimuthally averaged rainfall rates, illustrating the urban impact on the temporal evolution of TC rainfall from a Lagrangian perspective (Du et al., 2023). In all three scenarios, the evolution of rainfall follows a similar pattern, with most of the rainfall concentrated within a 200 km radius. Before landfall, heavy rain bands (>10 mm/h) are located between 70 and 200 km from the typhoon center, while after landfall, rainfall becomes concentrated within approximately 70 km of the core region. Although the overall trend is consistent, there are noticeable differences in the post-landfall stage.

To further explore the evolution of rain bands at different azimuthal angles, Fig. 6 also presents time-azimuth Hovmöller diagrams of average rainfall rates for the 70–200 km and 0–70 km radius bands. The results show that, compared to LU-1980, rainfall in the outer spiral rainband (70–200 km from the center) in LU-2020 and LU-2100 increases significantly 2–6 h after landfall within the typhoon's eastern and northeastern quadrants, aligning with urban areas (Fig. 6d-f). At the same time, rainfall within a 70 km radius intensifies and extends eastward in LU-2020 and LU-2100, increasing by about 25.5% and 23.5%, respectively, with deeper and more intense convection (Supplementary Fig. S6). Rainfall becomes more concentrated within the 70 km core region, while rainfall between 70 and 150 km from the center is lower than in LU-1980 (Fig. 6g-k), suggesting that urbanization may drive heavy rainfall closer to the typhoon's center. Compared to LU-1980, the rainfall peak in LU-2020 and LU-2100 increases by approximately 26.8% and 16.3%, respectively, and the peak occurs 1 h earlier. Although the rainfall peak in LU-2100 is lower than in LU-2020, the onset of heavy rainfall is earlier, and its duration is longer (Fig. 6j). Overall, urbanization increases rainfall intensity in urban coastal regions and advances the timing of peak precipitation, transforming the spatial pattern from inland- to coast-dominated enhancement.

3.1.2. Storm surge

Storm surge extent is influenced by many factors such as TC intensity, size, approach angle to the coast, and the RMW (Resio and Westerink, 2008). RMW typically occurs in the eyewall or its vicinity, where the strongest tangential winds are concentrated. The RMW exhibits a relatively stable pattern across the urbanization scenarios, typically located at approximately 60–70 km from the center in both pre- and post-landfall conditions (Supplementary Fig. S7). Given the limited variations in RMW and other TC structural parameters—including track, central pressure, and 10-m maximum wind speed—across urbanization scenarios, the corresponding differences in simulated storm surge heights are also minor, with peak surge changes generally within ± 0.2 m (Fig. 7).

Overall, although urbanization has a limited impact on the track and intensity of typhoon, it can significantly enhance inner-core rainfall by over 20%, a finding that is consistent with Du et al. (2023), thereby reshaping the spatiotemporal distribution of rainfall. Specifically, with intensified urban development, the rainfall peak becomes stronger and occurs earlier, leading to more concentrated



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Fig. 6. Time-radius Hovmöller diagrams of azimuthally averaged rain rates for a) LU-2020, b) LU-1980, and c) LU-2100; and time-azimuth Hovmöller diagrams of rain rates averaged over a 70–200 km radius for d) LU-2020, e) LU-1980, and f) LU-2100, as well as for a 0–70 km radius for g) LU-2020, h) LU-1980, and i) LU-2100; and j) averaged rain rate within a 70 km radius, k) averaged rain rate 6 h after landfall. The dashed grey line denotes the time of landfall.

precipitation over coastal areas. Notably, although the rainfall peak under the LU-2100 scenario is slightly lower than that in LU-2020, the duration of heavy rainfall is longer, reflecting a nonlinear response of rainfall evolution to different stages of urban growth. In contrast, the influence of urbanization on storm surge remains relatively limited.

3.2. Future hazards under climate change and urbanization (LU-2020 → CLIM-2100 → COMB-2100)

The CLIM-2100 and COMB-2100 simulations, both based on PGW-modified boundary conditions, reveal notable differences in typhoon characteristics compared to LU-2020. Most models project a westward shift in landfall location, apart from BCC-CSM2-MR, which simulates landfall closer to urban areas (Supplementary Fig. S8). As shown in Fig. 8a, b, before landfall, the ensemble mean of typhoon intensity and 10-m maximum wind speed under the PGW experiments are comparable to the LU-2020 control scenario, despite a considerable spread among individual ensemble members. In contrast, after landfall, all future simulations consistently demonstrate an increase in both maximum wind speed and storm intensity relative to LU-2020, with a multi-model mean central pressure reduction of 5.1 ± 2.6 hPa (mean ± 1 SD; 6/6 models show an increase). This is because the simulated typhoon, after reaching peak intensity, enters the weakening and landfall phase. Therefore, the observed changes primarily reflect differences in decay rather than re-intensification. Reduced post-landfall weakening under future warming is likely due to warmer land surface conditions that help sustain storm structure, leading to more prolonged impacts and elevated hazards.

Compared to CLIM-2100, the additional effect of future urbanization in COMB-2100 results in only minor adjustments in typhoon track, intensity, and maximum wind speed. During the hours surrounding landfall, the ensemble mean central pressure and wind speed exhibit a slight decrease across models. These modest changes indicate that while future urbanization exerts limited influence on the storm's overall track and intensity, its impact on wind field distribution and localized rainfall patterns may still be notable, warranting further examination.

3.2.1. Rainfall

The spatial distributions of total rainfall in most PGW runs closely resemble those of the control scenario, showing consistent patterns among ensemble members (Supplementary Fig. S9). Thus, the differences in rainfall between the control and PGW experiments are attributed to global warming rather than chaotic behavior (Taniguchi et al., 2015). According to Fig. 8c, the averaged azimuthal rain rate within a 200 km radius shows a significant increase throughout the typhoon event under future climate conditions (CLIM-2100), with a particularly pronounced enhancement after landfall. From landfall (09:00 UTC on 16 September) onwards, the multi-model mean rainfall rate increases by $44.4 \pm 10.2\%$ relative to the control scenario (LU-2020), with all six models showing an increase, indicating a robust intensification in rainfall intensity. This intensification is primarily attributed to elevated temperatures, which lead to higher moisture saturation, enabling the typhoon system to carry more water vapor and thus enhancing overall rainfall rates (IPCC, 2021). This pattern is consistent with global satellite observations (Guzman and Jiang, 2021), which show that rising sea surface temperatures and higher total precipitable water have contributed to increased TC rainfall rates. When future urbanization is further considered (COMB-2100), the mean rain rate during the first several hours after landfall becomes slightly higher than under CLIM-2100. Although not all models project higher peak intensities, the lower bound of rainfall across all models under COMB-2100 is consistently elevated compared to CLIM-2100. This suggests a small additional influence of future urbanization on rainfall intensity, although the magnitude of the response varies among models.

Further analysis (see Supplementary Fig. S10) reveals pronounced changes in the radial-vertical convective structure under future climate conditions. Together with enhanced moisture availability resulting from rising temperatures, these dynamical changes support strengthened convection and increased rainfall. Additionally, vertical velocity within the 50–150 km radius also intensifies, facilitating

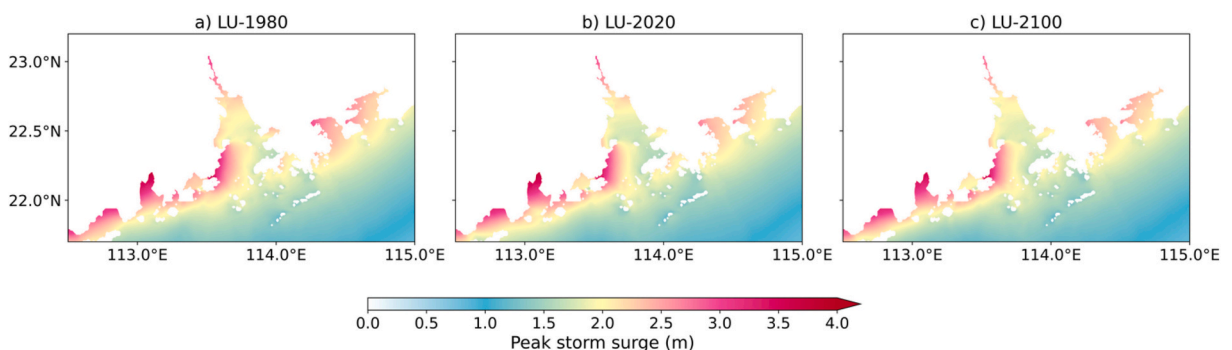


Fig. 7. Simulated peak storm surge heights under a) LU-1980 b) LU-2020, and c) LU-2100 scenarios.

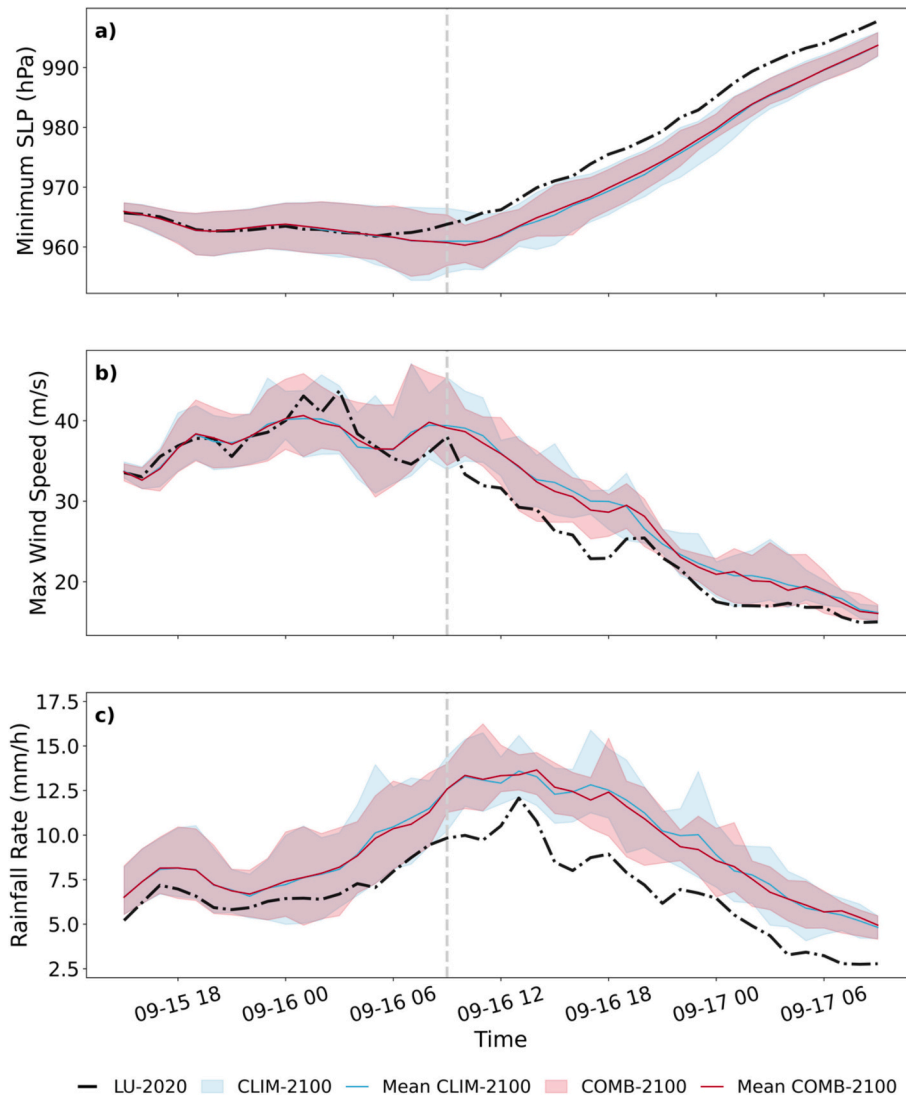


Fig. 8. Time series of a) minimum sea level pressure, b) maximum wind speed, and c) rainfall rate under the Climate-2100 (CLIM-2100) and Combined-2100 (COMB-2100) scenarios within a 200 km radius. Thin colored lines represent the mean of model results, while the black dash-dot line represents the Control Scenario (LU-2020). Shaded areas denote the range of model outcomes. The dashed grey line denotes the time of landfall.

stronger upward motion that supports increased rainfall intensity. This enhanced upward motion allows for more efficient transport of moisture to higher altitudes, where it condenses and contributes to precipitation. This interplay between thermodynamics and dynamics demonstrates how climate change influences extreme typhoon rainfall patterns, resulting in increased intensity and altered distributions. When future urbanization is further included, the overall convective structure remains broadly similar to the climate-only response, while enhanced vertical motion is evident within the typhoon inner-core region. This enhanced convection is consistent with the observed increase in rain rate within this region.

While all models consistently simulate intensified rainfall intensity near the typhoon center under future climate conditions, spatial distributions of accumulated precipitation still exhibit substantial inter-model variability, primarily driven by differences in typhoon tracks and rainfall localization. Nevertheless, the ensemble mean reveals a robust increase in cumulative rainfall over the urban core areas of the Greater Bay Area, with notable enhancements in cities such as Macao, Zhuhai, Guangzhou, Shenzhen, and Hong Kong (Fig. 9a-c). The additional increase in rainfall rates due to future urbanization further contributes to differences in accumulated rainfall. Within WRF Domain 3, the ensemble-mean cumulative rainfall rises from 164 mm (CLIM-2100) to 169 mm (COMB-2100), representing an increase of approximately 3.1%, while the maximum increases from 355 mm to 370 mm (+4.2%).

3.2.2. Storm surge

In addition to rainfall intensification, changes in storm surge behavior also play a crucial role in shaping compound flood hazards under future scenarios. Under PGW conditions, the simulation results indicate an expansion in RMW from 60 to 70 km to 90–100 km

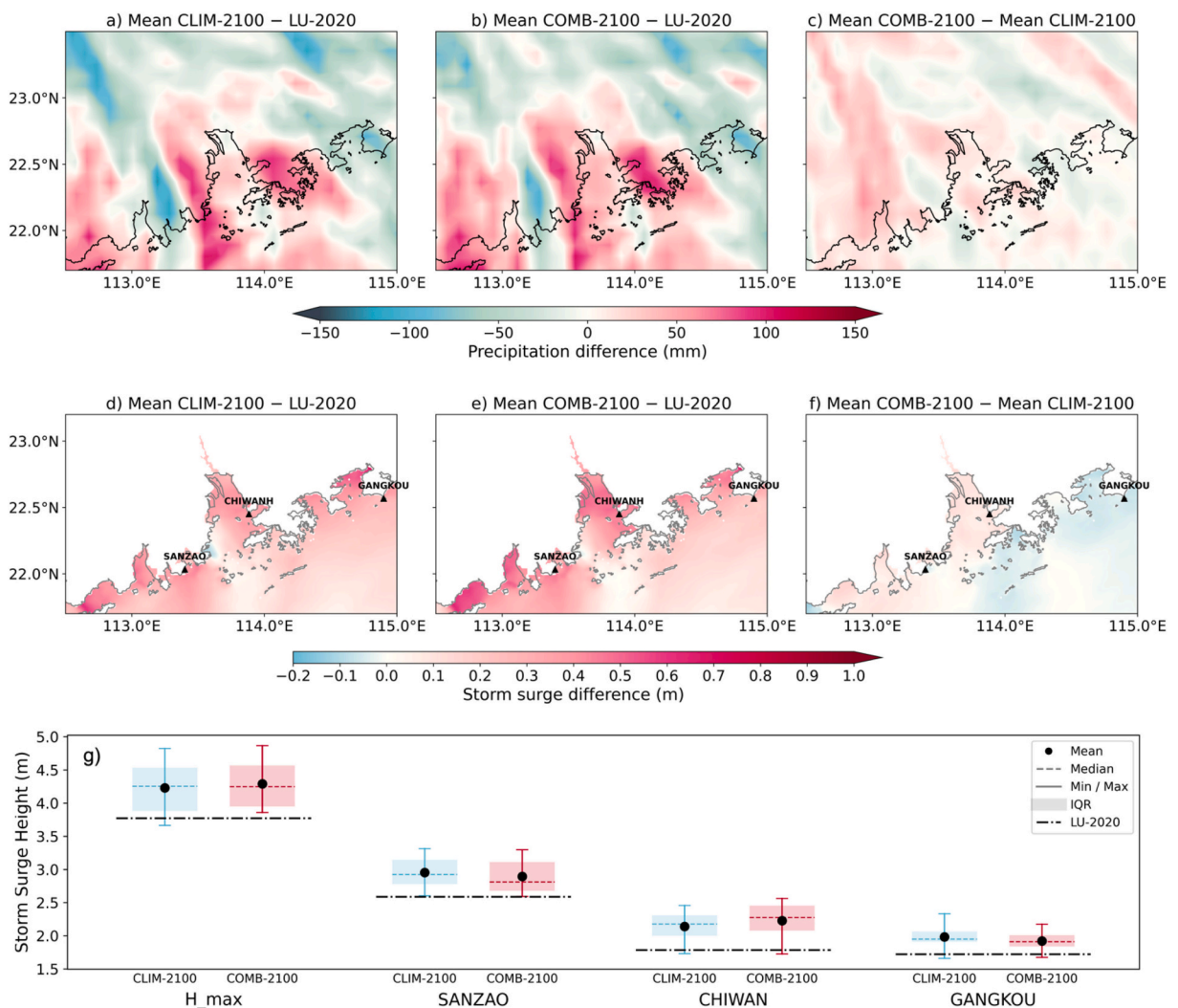


Fig. 9. Spatial distribution of ensemble-mean differences in accumulated rainfall (a–c) and peak storm surge height (d–f) between future scenarios and the control scenario (LU-2020). Panel (g) presents modified boxplots of maximum storm surge height across the study area (H_max) and at three tide gauge stations (SANZAO, CHIWAN, and GANGKOU), under the CLIM-2100 and COMB-2100 scenarios. Shaded areas denote the range of model results.

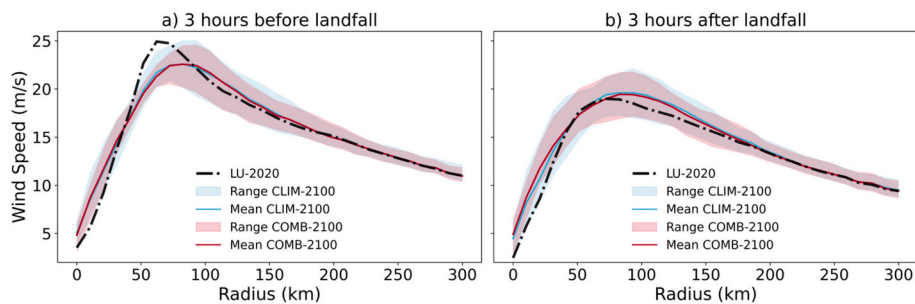


Fig. 10. Azimuthal averages of 10-m tangential wind speed under the Climate-2100 (CLIM-2100) and Combined-2100 (COMB-2100) scenarios: a) 3 h before landfall and b) 3 h after landfall.

(Fig. 10), reflecting an outward shift in the location of the maximum tangential wind. During the three hours preceding landfall, the average peak 10-m tangential wind speed decreases, while tangential wind speeds at larger radii increase, resulting in a more radially uniform wind field. This redistribution may reflect a structural adjustment of the typhoon under warmer environmental conditions, with the inner-core wind field becoming broader and the maximum tangential wind shifting outward. However, after landfall, the average tangential wind speeds under the future scenarios remain higher than those in the control, indicating that PGW conditions mitigate the typical decay of the typhoon post-landfall, which, as previously analyzed, leads to a slight increase in tangential wind speeds.

RMW is a key structural parameter that significantly influences storm surge near the coast during landfall (Chen et al., 2020). A broader RMW implies a wider high-wind area, potentially exposing coastal urban regions to strong winds for an extended period and heightening storm surge hazards in these areas. Under future climate conditions, lower central pressures, stronger 10-m maximum wind speeds, and the broader RMW collectively contribute to increased storm surge. Results indicate a widespread increase in surge height across the domain under climate change scenarios (Supplementary Fig. S11), with ensemble-mean differences reaching up to 0.6 m in some areas (e.g., Daya Bay; Fig. 9d). This signal is further supported by the boxplot summary in Fig. 9g, which presents the model spread at the domain-wide maximum and at three tide gauge stations under the future climate scenarios. The majority of ensemble members under CLIM-2100 project higher storm surges compared to the LU-2020 baseline, although the magnitude and spread of these increases vary across locations. The general agreement across models indicates a robust signal of climate change-induced surge intensification.

When future urbanization is further considered, the spatial pattern of storm surge differences exhibits a consistent west–east gradient across most models—surge enhancement is concentrated along the western coast of the Pearl River Estuary, while slight reductions occur along the eastern shoreline. Although the magnitude of urbanization-induced changes is modest (typically within ± 0.2 m), a systematic increase is still observed along the primary landfall impact region. These findings suggest that, while urbanization is not the dominant driver of surge intensification, it may still modify localized surge responses through changes in the wind field under a warming climate, with implications for compound flood hazards.

3.2.3. Compound Hazard assessment

To assess compound flood hazards under future scenarios, it is essential to jointly consider both hydrological (rainfall) and oceanic (storm surge) drivers. This section presents a two-dimensional hazard space to visualize and quantify the combined intensification of TC-induced hazards (Fig. 11). To ensure consistency and comparability across models, we use the core-region rainfall rate as the rainfall metric. It is defined as the average rain rate within a 200-km radius of the typhoon center during the critical landfall period (08:00–15:00 UTC). This time window is selected based on earlier analysis (Fig. 8c), which shows that the influence of urbanization on rainfall is most pronounced during the hours surrounding landfall, allowing its additional contribution under future climate conditions to be more clearly assessed. In contrast to spatially accumulated rainfall, which is highly affected by variations in typhoon tracks and localized precipitation patterns, the core-region rainfall rate serves as a more robust indicator of rainfall differences. When combined with storm surge processes, it provides a more representative characterization of compound flood potential.

As shown in Fig. 11, future climate change alone (CLIM-2100, in blue) leads to a noticeable shift towards higher values in both rainfall and storm surge, as evidenced by the rightward and upward displacement of the ensemble center. When future urbanization is further included (COMB-2100, in red), the ensemble center moves even further into the upper-right quadrant, indicating additional

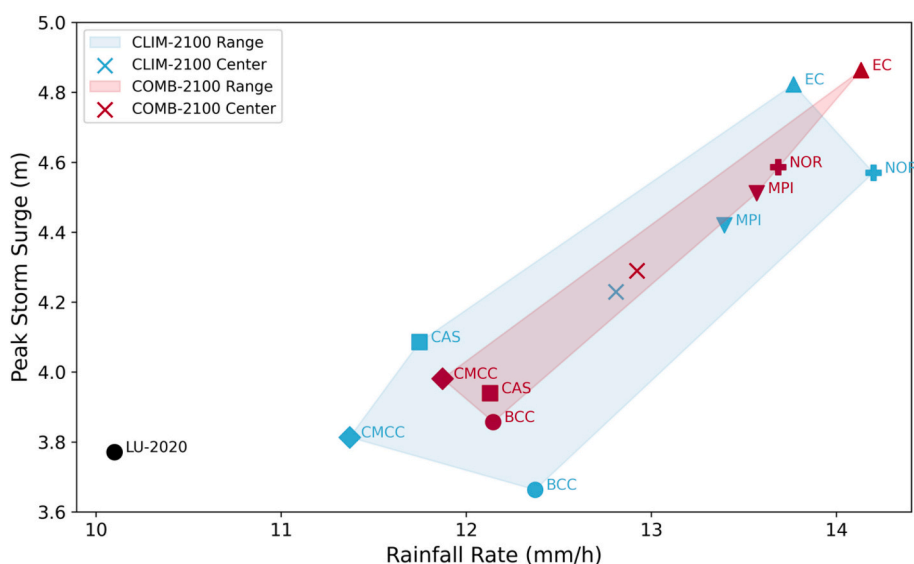


Fig. 11. Joint distribution of peak storm surge height and rainfall rate across all scenarios and models. Each dot represents an individual model realization, and the convex hulls delineate the envelope of compound hazard conditions under different scenarios.

intensification of compound flood hazards. Notably, the shaded region of the COMB-2100 scenario is smaller than that of CLIM-2100, suggesting a reduced inter-model spread. This contraction implies a more robust and consistent signal of compound hazard amplification under the combined influence of climate change and urbanization. Quantitatively, the ensemble mean shows that climate warming increases the core-region rainfall rate and peak storm surge by $26.8 \pm 11.4\%$ (from 10.1 mm/h to 12.8 mm/h; 6/6 models show an increase) and $12.1 \pm 12.0\%$ (from 3.8 m to 4.2 m; 5/6 models show an increase), respectively. Future urbanization further contributes additional increases of 0.9% and 1.4%, with increases occurring in 4/6 and 5/6 models, respectively.

Compound flood hazard changes are assessed by computing the Compound Hazard Index (CHI) for each model realization. Under future climate change alone, CHI increases by 7% to 32%, with a multi-model average increase of $19.2 \pm 11.2\%$. When future urbanization is additionally considered, CHI changes range from 11% to 34%, with the ensemble mean increase of $20.6 \pm 10.4\%$. All six models show an increase in CHI under both future scenarios. However, the additional effect of future urbanization relative to climate change alone is less consistent, with 4/6 models showing a further increase in CHI and model-specific changes ranging from -2.1% to $+4.7\%$.

4. Discussions and limitation

This study systematically explores how future climate warming and urbanization jointly reshape the flood hazard profile of a historically extreme typhoon—Super Typhoon Mangkhut—during its landfall phase in the Greater Bay Area (GBA). Our findings show that climate change is the dominant driver of compound hazard intensification, while future urbanization provides an additional, though relatively modest, contribution to rainfall and storm surge changes.

4.1. Sustained TC intensity and evolving Hazard dynamics

Under SSP5–8.5 conditions, warming significantly slows typhoon decay post-landfall, maintaining a central pressure ~ 5 hPa lower on average, with all six models showing a consistent increase in storm intensity. Such behavior is consistent with observational evidence and earlier PGW simulations (Lai et al., 2024; Li et al., 2024) and is likely driven by amplified land surface warming relative to the ocean, which increases sensible heat flux and sustains storm intensity over land. In contrast, core-region rainfall rates remain substantially elevated throughout the simulation, mainly due to increased atmospheric moisture that enhances latent heat release, strengthens convective organization, and promotes more efficient vertical moisture transport. Elevated storm intensity and rainfall rates could further contribute to more prolonged and extensive flooding. Notably, an expansion in the radius of maximum wind, in contrast to the contraction reported in some previous studies (e.g., Nellipudi et al., 2021), suggests that future TCs may influence a larger spatial footprint, increasing the exposure of coastal urban systems.

4.2. Urbanization effects on compound hazards and planning implications

Although the absolute contribution of urbanization to rainfall and storm surge intensification is modest ($\sim 1\%$), its effects are spatially concentrated in vulnerable areas. Despite the shift towards taller and denser urban development in the future, the overall effect of urbanization remains substantially smaller than that of climate change. Notably, Deng et al. (2025) reported a similarly modest regional-scale effect of urbanization on TC rainfall despite using a much stronger urban–nonurban contrast, with urbanization primarily redistributing rainfall rather than substantially increasing the regional total. These results highlight that even under strong climatic forcing, urban morphology can shape hazard distribution in meaningful ways—especially in cities with dense, low-lying development.

When rainfall and storm surge are considered together through the Compound Hazard Index (CHI), climate change alone increases the compound hazard by $\sim 19\%$ on average. With future urbanization included, the ensemble-mean increase reaches $\sim 21\%$. Although the additional contribution of urbanization is modest, even small changes in rainfall and storm surge may become consequential when they occur near critical drainage or infrastructure thresholds (Cotterill et al., 2026; Qqunta et al., 2026). These findings reinforce the importance of accounting for compound hazards in future flood risk assessments, rather than relying solely on historical single-hazard events. The substantial inter-model spread indicates considerable uncertainty in the magnitude of projected compound hazard changes. Nevertheless, all models project an increase in CHI relative to the control under both future scenarios, while the additional effect of urbanization is less consistent across models. Resilience planning should therefore consider a range of plausible hazard levels rather than relying solely on the ensemble mean.

4.3. Limitations and future directions

Several limitations should be acknowledged. First, this study focuses on a single typhoon event and its post-peak-intensity phase, which limits generalizability across storm types and trajectories. The present results are most directly applicable to intense landfalling TCs with characteristics and trajectories similar to Typhoon Mangkhut. Storm track and intensity can influence the spatial distribution and magnitude of rainfall and storm surge, and therefore their relative contributions to compound flood hazards. Future research should extend the multi-scenario PGW framework to a wider range of TCs to examine the applicability of these findings across different TC intensities. Second, sea-level rise, which could compound storm surge impacts by elevating background water levels and altering

the effective coastal geometry, thereby influencing surge dynamics, is not considered in the current simulations. By 2100, sea-level rise in the GBA is projected to range from a median of 0.7 m to a maximum of 1 m under the SSP5–8.5 scenario (Garner et al., 2021). Third, large-scale climate variability (e.g., El Niño–Southern Oscillation) is not explicitly considered in the current simulations. Fourth, future work could incorporate full 3D wind fields from WRF and two-way coupling between the atmospheric and storm surge models to better represent air–sea interactions. Fifth, the CHI provides a simplified measure of compound hazard based on rainfall and storm surge and is primarily intended for comparing relative changes across scenarios. It does not explicitly simulate the resulting inundation processes or account for the nonlinear interactions between rainfall, storm surge, drainage, and overland flow. Although normalization makes the two components dimensionless and comparable, the CHI does not have a direct physical unit or calibrated flood-impact interpretation. Future work should therefore incorporate coupled hydrological–hydrodynamic flood modelling to quantify changes in inundation extent and depth and provide a more direct assessment of compound flood impacts. Finally, while urbanization is considered in physical terms (e.g., land cover change), socio-economic exposure and vulnerability (e.g., population exposure, drainage capacity, and emergency response capacity) are not modeled, so this study focuses on hazard rather than risk and could be extended to risk assessments in future.

5. Conclusions

This study provides a physically consistent and high-resolution assessment of the combined effects and relative contributions of climate change and urbanization to compound typhoon flood hazards in a major coastal megaregion. By simulating the historical Super Typhoon Mangkhut under future climate and urbanization scenarios based on SSP5–8.5, we draw the following key conclusions:

1) Climate change significantly alters the typhoon's evolution during the critical landfall phase—the period most relevant to disaster impact. All six models consistently simulate stronger storm intensity from landfall onwards, with a multi-model mean central pressure ~ 5 hPa lower than the present-day simulation, indicating slower decay and consequently enhanced hazard potential.

2) Climate change and urbanization jointly intensify the typhoon's core-region (radius ≤ 200 km) rainfall rate and peak storm surge, with climate change being the dominant contributor. Climate change increases rainfall rates during landfall by $\sim 27\%$ and peak storm surge by $\sim 12\%$, while the additional effect of future urbanization is modest ($\sim 1\%$) and varies across models. Despite continued urban expansion and a shift towards taller and more compact urban forms, the overall urbanization effect remains substantially smaller than that of climate change.

3) Compound flood hazards increase substantially under future conditions, with the Compound Hazard Index (CHI) increasing by $\sim 19\%$ on average under climate change alone and $\sim 21\%$ when future urbanization is included. All six models project higher CHI relative to the present-day control under both future scenarios, although the additional effect of urbanization is less consistent across models.

These findings underscore the urgent need to update urban flood planning frameworks, moving beyond historical benchmarks to incorporate worst-case future compound events. Integrated, forward-looking modelling approaches—such as those developed in this study—are critical for informing infrastructure design, land-use zoning, and emergency preparedness in the era of climate-driven extremes.

Data sources

The observational data for typhoon track and intensity were sourced from International Best Track Archive for Climate Stewardship (IBTrACS) (Gahtan et al., 2024; Knapp et al., 2010). The model's rainfall evaluation utilized the hourly precipitation product from the near-real-time dataset of the China Meteorological Administration Land Data Assimilation System (CL-DAS-V2.0). This dataset, with a spatial resolution of $0.0625^\circ \times 0.0625^\circ$, is derived from an integration of ground-based, satellite, and other observational sources. The accuracy of this dataset has been rigorously assessed against observations from over 2400 national-level automatic weather stations across China, yielding an hourly precipitation RMSE of 0.94 mm/h, a bias of -0.004 mm/h, and a correlation coefficient of 0.72. The initial and lateral boundary conditions were derived from the NCEP FNL (Final) operational global analysis and forecast dataset, which is available on grids with a resolution of $0.25^\circ \times 0.25^\circ$ and a temporal interval of 6 h. Climate scenarios utilized in this study were obtained from the global climate models (GCMs) of the Coupled Model Intercomparison Project Phase 6 (CMIP6). The storm surge observation data is sourced from the National Marine Environmental Forecasting Center of China.

CRedit authorship contribution statement

Jingru Liu: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Zhan Tian:** Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Steven Dobbie:** Writing – review & editing, Supervision, Resources. **Andrew N. Ross:** Writing – review & editing, Supervision, Resources, Methodology. **Laixiang Sun:** Writing – review & editing, Supervision, Conceptualization. **Yuanong Gao:** Software, Resources. **Xianxiang Li:** Resources, Formal analysis. **Xiaoping Liu:** Resources, Formal analysis.

Author statement

J.L. designed the study, conducted the meteorological simulations and all analyses, and wrote the manuscript. J.S.D. and A.R. contributed to framing the paper and provided methodological guidance. T.Z. and L.S. contributed to the overall study design and

provided substantial input to manuscript revision. Y.G. performed the storm surge simulations. X.Li contributed the urban canopy parameter settings. X.Liu provided the land use data and technical assistance. All authors contributed to reviewing and approving the final version.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.uclim.2026.103199>.

Data availability

Data will be made available on request.

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