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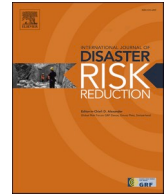
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# Storm surge responses in Macau: Early warnings and soft adaptation

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## ABSTRACT

Few coastal metropolises other than Macau have experienced storm-surge flooding in their central districts three times in the past decade. This paper examines governmental and citizen responses to Typhoons Hato (2017), Mangkhut (2018), and Ragasa (2025), drawing primarily on resident interviews to assess how Macau has strengthened its storm surge response over a short period. A major improvement is the substantially earlier issuance of typhoon signals. Our typhoon model analysis shows that the critical escalation from Signal No. 3 to No. 8 occurred more than 10 h earlier for Mangkhut and Ragasa than for Hato. Evacuations increased markedly at Signal No. 10 during Ragasa, a pattern not observed for Hato or Mangkhut. The appropriateness of warning issuance for the three events is discussed in detail, highlighting the necessity of precautionary early warnings, as reliance on weather predictions alone is insufficient to ensure safe evacuation. Although no major coastal defenses, such as tall seawalls, have been built since Hato, a suite of soft measures—including earlier warnings, government-led evacuations, storm-surge warning posts, water-level stations, portable floodgates, mangrove afforestation, and residents' memories of past inundation—reflects enhanced resilience among authorities and citizens. Accordingly, despite substantial storm-surge damage, respondents evaluated recent government disaster management positively. This study provides an external assessment of Macau's mitigation efforts, with implications for other typhoon-prone coastal cities.

## 1. Introduction

Evacuation behavior during tropical cyclones reflects a complex interplay of risk perception, social influence, and resource availability [1]. Social influence—particularly the perceived availability of support networks—significantly shapes evacuation decisions [2]. Central to this process is the role of government agencies, as effective evacuation depends on the issuance of timely and reliable warnings [3]. There are numerous cases in which large-scale evacuations have been successfully carried out through strong support from government agencies, volunteer groups, and other organizations, particularly for residents who were uncertain about whether to evacuate [4]. Timely and appropriate evacuation instructions issued by the authorities play a crucial role in residents' evacuation decisions, as these studies indicate.

However, trust in authorities is fragile. Frequent false alarms can trigger a “cry wolf” effect, diminishing the perceived reliability of future alerts [5,6]. Beyond trust, the clarity of communication is also critical. Because phenomena such as storm surges are difficult for the public to conceptualize, it is insufficient for meteorological agencies to rely solely on technical terminology [7,8]. Similarly, visual

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tools such as the “cone of uncertainty” are often misinterpreted, with residents mistakenly assuming that areas outside the cone are entirely safe [9,10]. Broadcast meteorologists have noted the challenge of translating technical information into guidance that is accessible and actionable for non-expert audiences, underscoring the need for clearer plain-language summaries [11,12].

Even when risk is accurately understood, physical and cultural barriers to evacuation remain. Many residents delay evacuation due to economic concerns, fearing that their primary means of livelihood may be lost to theft or storm damage in their absence [5]. The effectiveness of a warning is often shaped by its cultural resonance, as messages that are purely technical and fail to engage with the spiritual, psychological, or cultural context of the population are frequently ignored [13]. Despite extensive early warning systems and thousands of available shelters, many residents failed to evacuate during Cyclone Sidr—a Category 5-equivalent storm that struck Bangladesh in 2007—resulting in significant loss of life [14]. Consequently, fostering greater trust between citizens and public officials is essential for increasing pre-disaster evacuation rates [1,15].

To elucidate the complex interplay between government and citizen responses, this research emphasizes the uniqueness of Macau's typhoon early warning system. Macau, located in the Pearl River Delta, was originally a small fishing village before Portugal established a permanent settlement there in 1557. Since then, it has developed into a coastal metropolis with one of the highest concentrations of wealth in the world. However, its location—directly exposed to the open sea and subject to frequent typhoons—makes Macau highly vulnerable to storm surges. Notably, within the past decade, the city has experienced storm-surge inundation three times: from Typhoon Hato (2017), Mangkhut (2018), and Ragasa (2025).

Even within typhoon-prone regions such as the East and Southeast Asia, there is no unified approach to warning protocols. For example, in Vietnam, typhoon evacuation warnings are classified into Levels 1 to 5, and when higher-level warnings such as Level 4 or 5 are issued, authorities are legally empowered to enforce the evacuation of residents (Government Decree No. 66/2021/ND-CP). By contrast, in Japan, although the Japan Meteorological Agency (JMA) issues typhoon warning signals on a five-level scale similar to that of Vietnam, evacuation measures issued by local authorities remain advisory in nature and lack legal enforceability.

In Macau, before Typhoon Hato in 2017, typhoon evacuations, like those in Japan, were advisory; however, after a 2020 revision (Law No. 11/2020), the Chief Executive can now issue legally enforceable evacuation orders to residents. The Macao Meteorological and Geophysical Bureau (SMG) employs a distinctive system of numbered Tropical Cyclone Signals to warn the public of wind threats posed by approaching typhoons. The system consists of five main signals—No. 1, No. 3, No. 8, No. 9, and No. 10—each corresponding to a different threat level, primarily determined by the expected wind speeds (Appendix Table A1). This system was originally implemented in Hong Kong. The unique sequence was created by pruning a historical 1-to-10 scale, specifically by retiring redundant distance markers and consolidating four different gale-direction signals into a single Signal No. 8 to improve public clarity [16].

In particular, the upgrade from Signal No. 3 to No. 8 represents the most significant shift in the management of social and economic activities in Macau [17]. For example, when No. 8 or higher is hoisted, all schools and offices are closed, and the long bridges connecting Macau's two main islands are also shut down. The closure of these bridges greatly affects Macau's economy, which is heavily reliant on casino tourism. In addition, following the severe storm-surge damage caused by Typhoon Hato in 2017, the SMG revised its storm-surge warning system. It now issues storm-surge signals to residents using a five-tier classification of Blue, Yellow, Orange, Red, and Black (Table A1).

As external observers, we examine how the Macau government and the public have responded to recent major typhoons and assess the effectiveness of these responses. Since Typhoon Hato—particularly in efforts to mitigate storm-surge impacts—Macau has steadily strengthened its disaster resilience, making its experience especially valuable for other coastal metropolitan areas exposed to tropical cyclones. This study also addresses ongoing challenges in disaster response and preparedness in anticipation of stronger typhoons in the future.

## 2. Methodology

In this paper, residents' accounts were used to assess evacuation behavior, and numerical simulation outputs were employed to describe the meteorological conditions associated with the three typhoons (Hato, Mangkhut, and Ragasa)—factors that are critical to individual decisions. This section outlines these methodological approaches.

### 2.1. Targeted typhoon events

#### 2.1.1. Typhoon Hato

Typhoon Hato struck Macau in August 2017 and was one of the strongest storms to impact the Pearl River Delta. It produced nearly 3 m of inundation—the highest level recorded since 1925. Its forward speed, approximately 32.5 km/h, was unusually fast compared with other typhoons of similar intensity, complicating forecasting efforts and reducing warning lead times [17–19]. Nearly half of the city lost access to water and electricity, bringing businesses and public transportation to a standstill. In addition, casinos—on which the local economy heavily depends—experienced power outages and, in some areas, flooding, resulting in the greatest economic losses ever recorded in Macau. Public dissatisfaction with the government's response led to the resignation of the weather bureau chief. In particular, delays in issuing typhoon warning signals intended to prompt resident evacuation provoked strong public criticism [20–22].

#### 2.1.2. Typhoon Mangkhut

Typhoon Mangkhut struck in September 2018 and also caused storm-surge flooding in Macau's downtown areas. Although the peak water level was lower than that observed during Typhoon Hato, Mangkhut's much larger size resulted in a more extensive inundation

area [23]. In sharp contrast to the response to Hato, public perceptions of the government's handling of Mangkhut were more favorable, as authorities were viewed as acting more promptly and decisively [24]. Moreover, economic losses were less than one-tenth of those caused by Typhoon Hato [25], which appears to have further reduced public dissatisfaction.

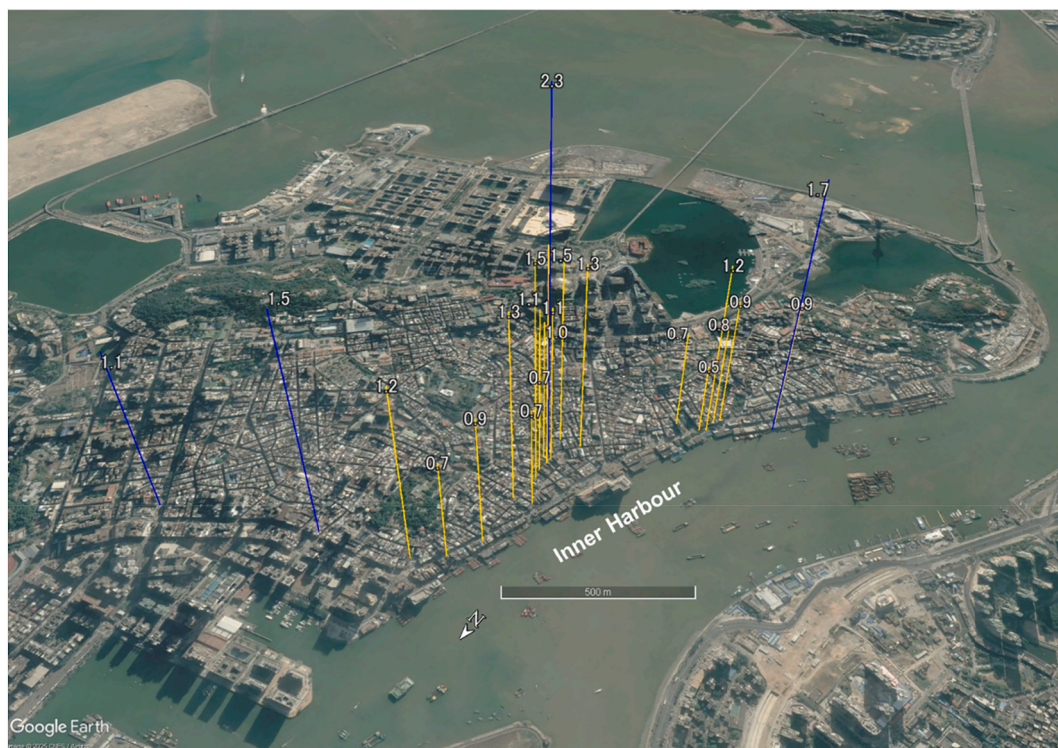
### 2.1.3. Typhoon Ragasa

Typhoon Ragasa, which occurred in September 2025, was the strongest typhoon to form in the Western North Pacific that year, with a minimum central pressure of 905 hPa, according to the Japan Meteorological Agency (JMA). The storm caused widespread damage across the Philippines, Taiwan, southern China, Hong Kong, and Macau. In Macau, downtown areas experienced more than 1 m of inundation due to storm surge. Following the issuance of a Red Storm Surge Warning, electricity supplies in low-lying areas were deliberately shut down as a precautionary measure [26]. Signal No. 10 was raised and remained in effect for a record of 10.5 h [27]. Despite the storm's intensity, no deaths or severe injuries were reported [28].

## 2.2. Questionnaire-based survey

We conducted interviews primarily with residents of Macau's Inner Harbour area, the city's first harbour, which historically supported cargo shipment, inland river transport, and the berthing of fishing vessels (Fig. 1). The Inner Harbour area lies below 2 m above mean sea level [18,19], making it particularly vulnerable to storm-surge inundation. We conducted resident surveys after Typhoon Hato in 2017 and Typhoon Mangkhut in 2018 (see Appendix Table A2). To allow comparison with those results, we asked residents similar questions about one month after Typhoon Ragasa in 2025, as shown in Table 1. The questionnaire was prepared in Cantonese (Traditional Chinese), and the interviews were conducted face-to-face in Mandarin (Standard Chinese). We obtained responses from 28 participants ranging in age from their 20s to 60s. The sample size is not necessarily large; therefore, uncertainty in generalization is unavoidable. However, the survey was conducted at locations within the relatively small area of the Inner Harbour where flooding actually occurred (Fig. 1). As a result, the responses are considered to be reasonably representative of the opinions of people who needed to take action during storm-surge events.

In addition, we asked whether storm-surge flooding had occurred at the interview location, and, when respondents were able to recall the inundation level, we measured the reported water depth and recorded the geographic coordinates, as shown in Fig. 2. Many respondents were running businesses, and because their homes also served as workplaces, we were able to collect comparatively abundant evidence. They appear to have recognized the water level either by directly witnessing the water rising inside buildings or by observing water marks left on the walls. Inundation depths ranged from 0.5 to 1.5 m above ground level, which was slightly lower than those measured in our survey after Typhoon Hato [17] (Fig. 1). Inundation depths tended to be greater at slightly inland locations than



**Fig. 1.** Survey location. The yellow and blue bars indicate the inundation depths (meter) in Macau's Inner Harbour area caused by Typhoon Ragasa in 2025 and Typhoon Hato in 2017, respectively. (Background imagery (2020/1/3): © Google Earth).

**Table 1**

Questions used in the resident interviews conducted in Macau's Inner Harbour area after Typhoon Ragasa.

Demographics
Age range: 20–34 (7), 35–49 (10), 50–64 (4), over 65 (7)
Gender: Male (16), Female (12)
Questionnaire items
Q1. What typhoon signal was in effect at that time?
Q2. Where did you evacuate?
Q3. For those who evacuated: Why did you decide to evacuate? (multiple answer possible)
Q4. For those who NOT evacuated: Why did you NOT decide to evacuate? (multiple answer possible)
Q5. Which typhoon did you feel as the strongest?
Q6. Which typhoon caused your house to be flooded by storm surge? (multiple answer possible)
Q7. Compared to Typhoons Hato and Mangkhut, do you think Macau's government disaster response has improved?
Q8. What kind of disaster prevention measures do you hope? (multiple answer possible)
Q9. What improvements of government disaster response you have noticed?



**Fig. 2.** Inundation depths inside buildings, identified through resident interviews: (a) a port warehouse office, (b) a fish shop, (c) a restaurant, and (d) a pharmacy.

along the coastline, indicating that the lowest ground lies somewhat inland.

### 2.3. Numerical modeling for estimating typhoon wind and pressure fields

Whether residents choose to evacuate or stay, and whether authorities issue warnings, depends on the meteorological conditions. METAR data are standardized reports of current weather conditions at airports used primarily in aviation. In Macau, METAR data from the airport were available during Typhoons Hato and Mangkhut. However, the observational data during Typhoon Ragasa have not been released. Accordingly, in the next section, which analyzes evacuation timing and meteorological conditions, Ragasa is examined using the output of a numerical model. Therefore, using the model shown in Fig. 3—which integrates a global weather reanalysis model with a parametric typhoon model—we estimate the wind speeds and pressure deficits during each typhoon. This model was originally developed by [29] and [30] for calculating storm surges and high waves generated by tropical cyclones, but in this study, we use only the component that extracts the meteorological conditions.

The novelty of this method lies in its ability to simultaneously capture both the broad-scale meteorological field and the intense wind field near the typhoon center. For the global weather reanalysis, the model employs the ECMWF Reanalysis v5 (ERA5), which provides hourly estimates of atmospheric, land, and oceanic variables from January 1940 to the present. ERA5 operates on a  $0.25^\circ$  grid (approximately 27 km), which is too coarse to resolve the fine-scale structure of a concentric low-pressure system. Therefore, the

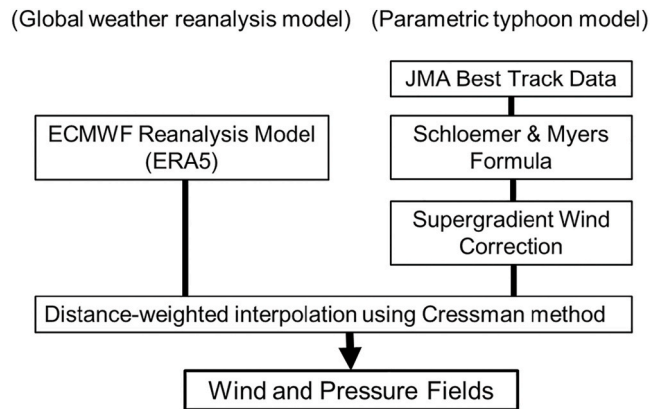


Fig. 3. Flowchart of the global weather-parametric typhoon coupling model.

typhoon's central region is replaced with an empirically derived parametric typhoon model—the Schloemer and Myers formula—applied over a fine grid with a resolution of  $0.005^\circ$  (approximately 550 m). The model also incorporates supergradient winds, which occur near the typhoon center and exceed the gradient wind speed. The typhoon records were obtained from the JMA best-track data. Although the best-track data are generally provided at 6-h intervals, the typhoon locations, central pressures, and radii are interpolated to hourly values in the model. Fig. 4 shows the sea-level pressure and wind-speed outputs at the time when each typhoon was closest to Macau.

Table 2 shows the results of the Root Mean Squared Error (RMSE) calculated for the 24-h time-series data before and after the peak of Typhoons Hato and Mangkhut. The wind speed error is less than 4 m/s, and the pressure error is approximately 2 hPa, indicating that the model demonstrates high estimation accuracy.

For Typhoon Ragasa, partial comparison with model simulations is possible because SMG has published a meteorological report [27]. Observations at the airport are not presented, but a maximum wind speed of 23.3 m/s was recorded at nearby Ká-Hó area. The SMG report also states that the minimum observed pressure in Macau was 982.3 hPa. Our numerical model results for Typhoon Ragasa show a wind speed of 26 m/s and a pressure of 983 hPa, indicating very high accuracy when the peak values are compared.

#### 2.4. Pre-landfall forward speed estimation

The forward speed of a typhoon is an important factor considered by meteorologists and government authorities when determining whether to upgrade typhoon warning signals. In this study, the pre-landfall forward speed is estimated using the code developed in our previous work [31,32].

The landfall point is identified as the intersection between the typhoon track and the coastline. The wind speed at landfall is derived by interpolating the JMA Best Track data covering the period 1977–2025 between the two points immediately before and after landfall. The forward speed is then calculated by dividing the distance between these two points by the corresponding time interval (i. e., 6 h). To encompass Macau and neighboring regions, the coastline is simplified as a single straight line connecting  $112.5^\circ\text{E}$ ,  $21.5^\circ\text{N}$  and  $114.5^\circ\text{E}$ ,  $22.5^\circ\text{N}$ , with an approximate length of 235 km.

### 3. Results

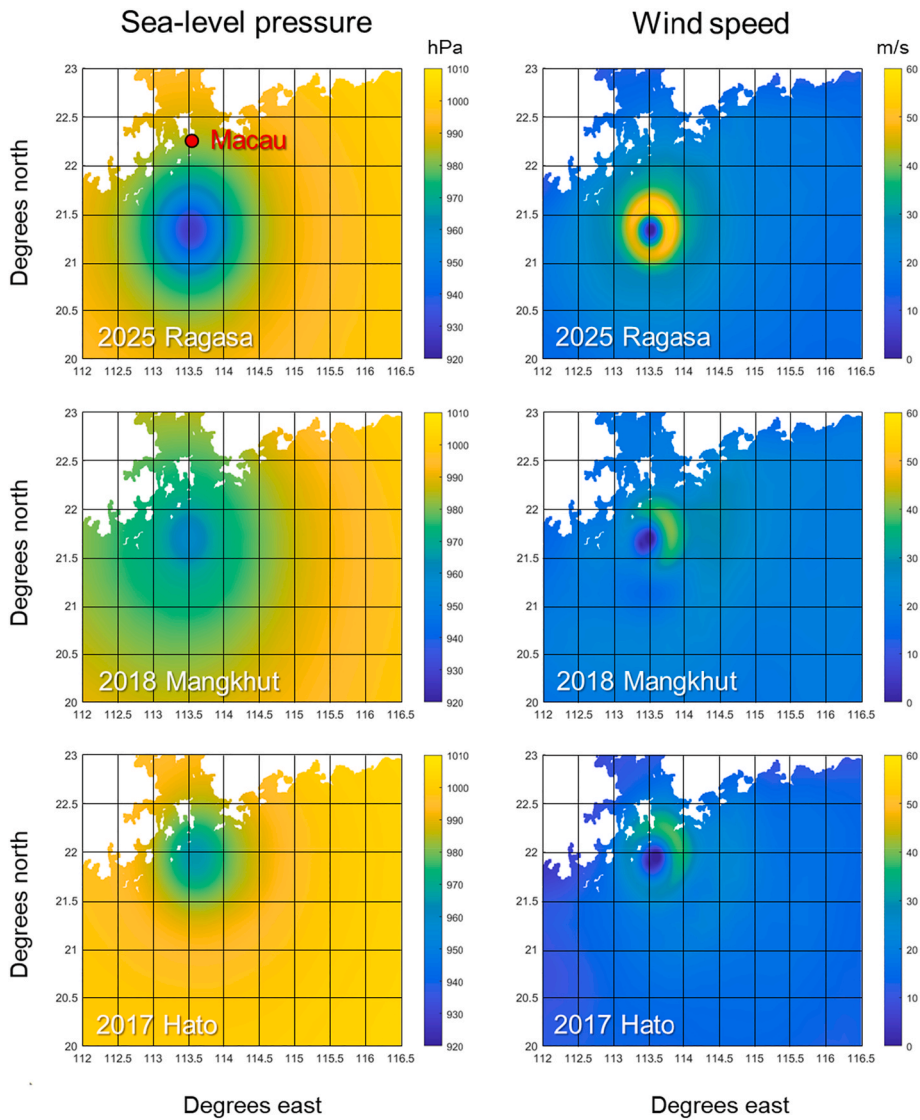
In the Inner Harbour area—Macau's most storm-surge-vulnerable district—we interviewed residents about their responses during Typhoon Ragasa and their views on government disaster management. The interview results are presented in Figs. 5, 6, and 7.

#### 3.1. Respondents' actions during Typhoon Ragasa

While 17.9% of respondents did not evacuate, the others took some form of evacuation action after Signal No. 1, suggesting that the number of evacuees was not small (Fig. 5. Q1). The largest number of residents evacuated at Signal No. 10, followed by Signals No. 3 and No. 8. It is noteworthy that no respondents evacuated at Signal No. 9, and that this number was even lower than at Signal No. 1.

Half of the respondents reported evacuating to their own homes, followed by upper floors of houses and neighbors' houses (Q2). According to the responses to Q1, it appears that many individuals returned home after Signals No. 3, 8, and 10 were issued. However, despite the availability of 17 designated evacuation shelters in Macau [33], none of the respondents reported using them. In our interviews, we did not find any cases in which the authorities instructed residents to evacuate to designated evacuation buildings; instead, in most cases, they recommended that residents return home or remain in their homes.

Several factors influence evacuation during typhoons, and housing vulnerability is one of them [34]. In Macau, most homes are reinforced concrete and unlikely to collapse in strong winds, which likely encouraged residents to stay home. Higher-income households also tend to evacuate to neighbors rather than public shelters, while lower-income groups rely more on public facilities



**Fig. 4.** Sample outputs illustrating when peak intensity occurred in Macau during the approaches of Typhoons Ragasa, Mangkhut, and Hato. The spatial extent of the simulation is approximately 330 km in the north–south direction (20–23°N) and 460 km in the east–west direction (112–116.5°E).

**Table 2**  
Comparison between airport observations and numerical modeling results.

Metric	2017 Hato		2018 Mangkhut	
	Wind speed	Pressure deficit	Wind speed	Pressure deficit
RMSE	3.8 m/s	2.1 hPa	1.1 m/s	1.9 hPa

Note: The meteorological data were extracted from the University of Wyoming's Global Surface Data. The instrument installation location is as follows.

Macau International Airport Location: 22.20N 113.53E, Height: 59 m.

[35]. Given Macau's high-income population, public shelter use is therefore expected to be low. Concerns about potential damage to critical infrastructure, such as power generation and healthcare facilities, also influence decisions to evacuate to outdoor areas (Lamadrid et al., 2025).

Evacuation instructions issued by the government and disseminated through television and radio were the primary trigger for evacuation decisions, influencing 60% of respondents (Q3). In addition, 16% appear to have based their decision on the typhoon

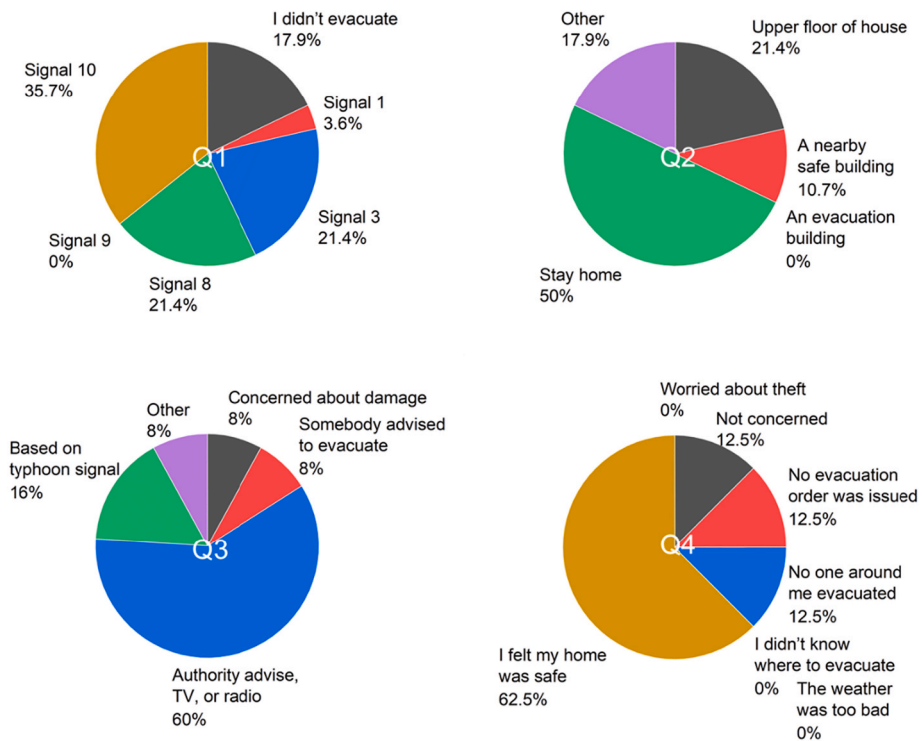


Fig. 5. Results of the interview survey (Q1–Q4) (See Table 1 for the list of question items.).

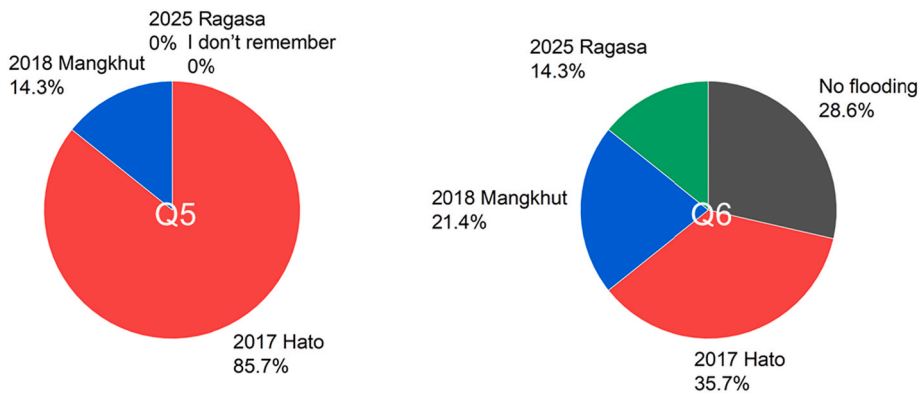


Fig. 6. Results of the resident interview survey (Q5–Q6) (See Table 1 for the list of question items.).

signals issued by the SMG. Thus, a total of 76% of respondents relied on government instructions, indicating a high degree of dependence. According to official sources, 3236 people evacuated following the government's evacuation advice [36].

In Q4, respondents who did not evacuate stated that they believed their homes were safe, which is consistent with the large number of 'stay home' responses in Q2. Meanwhile, 12.5% of respondents said they did not feel concerned. This is likely due to their previous experiences of being unaffected by Hato, Mangkhut, and other recent typhoons. Furthermore, as observed in both Q3 and Q4, about 10% of respondents were influenced by whether people around them chose to evacuate. It is well recognized that individuals' decisions are greatly affected by the choices of their neighbors [37,38]. There were no respondents who refrained from evacuating out of fear of theft. This contrasts with findings from countries such as Thailand, the Philippines, and other developing nations, where fear of theft is a major reason for staying home during disasters [15,39]. In this way, the perception that staying at home is dangerous can coexist with the opposing view that remaining at home is the safest option [40].

### 3.2. Respondents' recollection of typhoon intensities

Because Typhoons Hato, Mangkhut, and Ragasa all affected Macau within the relatively short period of 2017–2025, all respondents

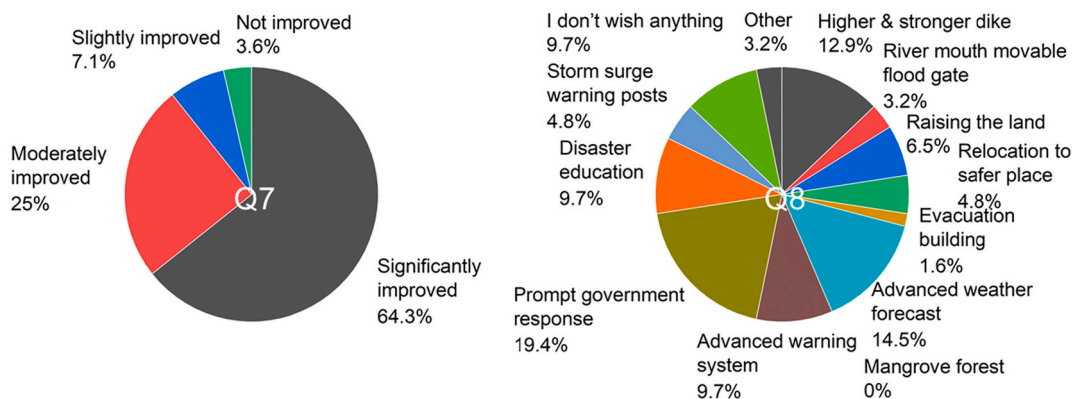


Fig. 7. Results of the resident interview survey (Q7–Q8) (See Table 1 for the list of question items.).

remembered each event clearly. Among the three typhoons, the largest number of respondents indicated that Typhoon Hato in 2017 was the strongest, followed by Mangkhut in 2018. None of the respondents identified Typhoon Ragasa in 2025 as the strongest (Fig. 6 Q5). The proportion of respondents who reported storm-surge flooding at their residence during Typhoon Ragasa was 14.3%, which is slightly lower than during Hato (35.7%) and Mangkhut (21.4%), but still a notable figure (Q6). It is also evident from Table 2 that Typhoons Hato and Mangkhut were stronger than Ragasa. For example, the model-estimated maximum wind speeds were 26 m/s for Ragasa and 36 m/s for Hato, suggesting that Hato was about 1.38 times stronger than Ragasa (Table 2). Because storm-surge height is proportional to the square of wind speed, a simple calculation suggests that Hato's storm surge would reach roughly 1.9 times that of Ragasa. This is broadly consistent with the storm-surge distribution shown in Fig. 1. These differences in wind intensity and the severity of inundation are likely to have been vividly remembered by the residents.

### 3.3. Residents' opinions on government response and disaster management

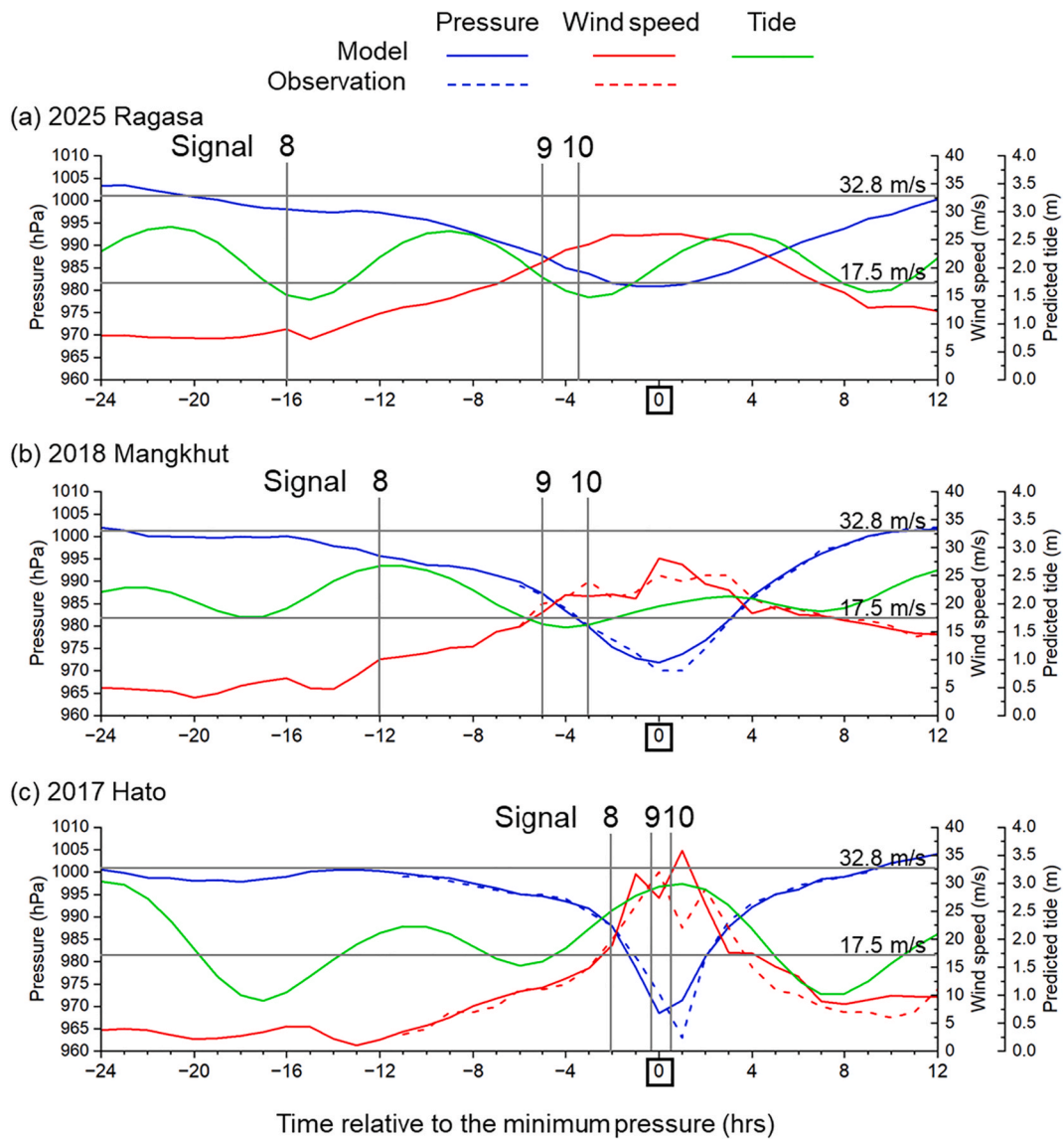
In response to the question of how the government's response during Typhoon Ragasa compared with that during Typhoons Hato and Mangkhut, about two-thirds of the respondents answered that it had improved significantly (Fig. 7 Q7). Regarding the aspects in which the response had improved, respondents mentioned various points. For example, during Typhoon Ragasa, the power outage lasted only about 4–6 h—much shorter than the three days experienced during Typhoon Hato. They also noted improvements in the warning system, including the quicker issuance of evacuation instructions; the installation of drainage pumps to remove floodwater; the deployment of portable floodgates; government patrols or warning announcements that urged residents to return home and prohibited them from remaining in shops; and the prompt post-typhoon cleanup in the city.

Fig. 7 Q8 indicates that respondents hold a wide range of views regarding future governmental responses to typhoons and disaster management. It is noteworthy that many respondents called for strengthening non-structural measures, including “prompt government response,” “advanced weather forecasting,” “advanced warning systems,” and “disaster education.” With regard to structural measures, “higher and stronger dikes” received a relatively high level of support (12.9%), whereas expectations for “river-mouth movable floodgates” and “raising the land” were low. This contrasts with the results of a survey conducted by the authors among 200 residents in Jakarta communities frequently affected by coastal flooding, in which 92% favored reinforcement and heightening of existing seawalls, and 49% supported the construction of a giant seawall surrounding Jakarta Bay [41–43]. Only 1.6% of respondents expressed a need for evacuation buildings, consistent with the absence of evacuees reported in Fig. 5 Q2.

## 4. Discussion

### 4.1. Evacuation signal timing

As noted earlier, during Typhoon Hato in 2017, delays in the government's response led to severe criticism of evacuation measures, ultimately resulting in the resignation of the chief of the meteorological authority. However, according to the results of our typhoon model and observations at Macau International Airport (Fig. 8), the timing of signal issuance closely corresponds to the wind speed thresholds for Signals No. 8 and No. 10—17.5 m/s and 32.8 m/s, respectively (Table A1). Although the resignation was likely prompted by accountability for the outcome, such criticism is not necessarily justified from this threshold-based perspective. Typhoon Hato's significantly higher approach speed and rapid intensification also likely rendered the delayed issuance of typhoon signals a critical factor [17,44]. The atmospheric pressure over Macau at the time of landfall is estimated to have been in the range of 960–970 hPa (Fig. 8). Although this represents a low-pressure system, it does not qualify as anomalously low. Despite this, a remarkably severe storm surge occurred, with water levels exceeding 2 m above the road surface. This outcome can be attributed in part to unfavorable timing, as the typhoon's landfall coincided with the peak of the astronomical tide (Fig. 1). The rapid intensification of the typhoon, coincidence with the peak astronomical tide, and delayed warnings likely explain why an overwhelming majority of respondents



**Fig. 8.** The issuance times of Signal No. 8 or above for the three typhoons, along with numerically estimated and observed pressures and wind speeds in Macau. The times are aligned relative to the timing of each typhoon's minimum central pressure. Wind speeds of 17.5 m/s (63 km/h) and 32.8 m/s (118 km/h) correspond to the reference thresholds for issuing Typhoon Signals No. 8 and No. 10, respectively. The astronomical tide was estimated using WXTide32 and adjusted to Macau's reference tidal level.

(85.7%) identified Hato as the strongest of the three typhoons (Fig. 6 Q5).

In contrast, Signal No. 8 was issued 12 h before the time of lowest pressure for Typhoon Mangkhut in 2018 and 18 h before that for Typhoon Ragasa in 2025. Therefore, it is considered that the warnings for Typhoons Mangkhut and Ragasa were issued based on a highly precautionary judgment, rather than being strictly determined by the official wind speed criteria (Table A1). Further discussion of the timing of these decisions is provided below.

Fig. 9 combines the results of the present and previous surveys [24] to compare the timing of residents' evacuation during the three typhoons. Notably, the largest number of evacuations occurred at Signal No. 8 during Typhoons Hato and Mangkhut, whereas evacuation was most prominent at Signal No. 10 during Typhoon Ragasa. To examine the reasons for these differences, the relationships between the timing of typhoon signals and the spatial positions of the typhoons are analyzed based on Figs. 10 and 11.

Fig. 10 shows how much earlier the other signals were issued relative to the issuance time of Signal No. 10. A longer lead time is desirable, as it provides residents with more time to evacuate. In particular, Signal No. 8 plays a critical role in residents' evacuation decision-making [17]; however, during Typhoon Hato, the lead time relative to Signal No. 10 was only 2.5 h. In contrast, the lead times were much longer during Typhoons Mangkhut and Ragasa, at 9 h and 12.5 h, respectively. Few people evacuated at Signal No. 8 during Typhoon Ragasa, possibly because wind speeds were only about 10 m/s (Fig. 8) and were not perceived as threatening.

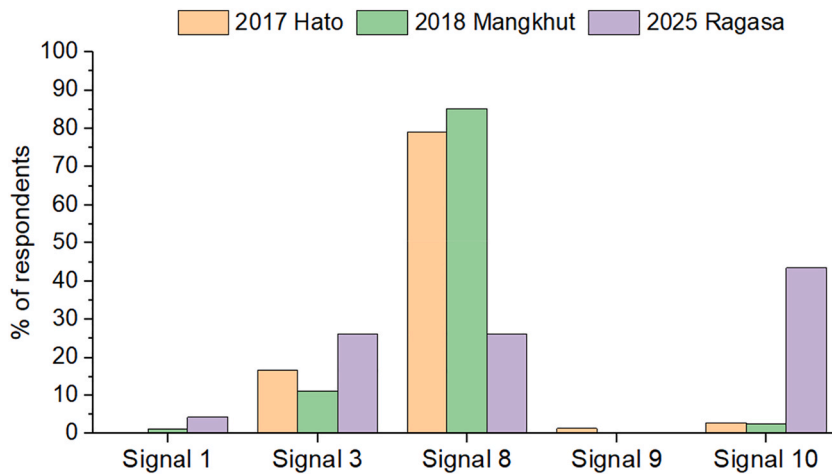


Fig. 9. Responses on the timing of residents' evacuation during the three typhoons.

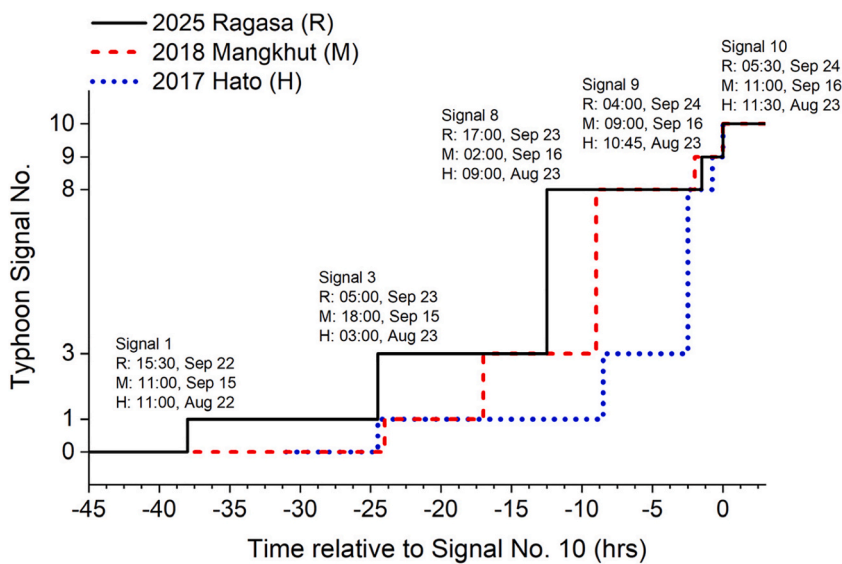


Fig. 10. Timing of signal upgrades from No. 1 to 10 during the three typhoons. The times are aligned relative to the issuance of Signal No. 10 for each typhoon.

The lead time between Signals No. 9 and No. 10 was short for all typhoons, ranging from 45 min to 2 h. In addition, as shown in Fig. 9, very few people begin evacuating at Signal No. 9, suggesting that its placement between No. 8 and No. 10 may warrant reconsideration. In addition, Signals No. 8 and No. 9 share the same wind-speed criteria (Table A1), making them difficult for the public to distinguish.

Fig. 11 shows the six-hourly positions and central pressures of the three typhoon centers based on the JMA Best Track Data. The figure also indicates the estimated locations at which Signals No. 8 and No. 10 were issued. First, with regard to typhoon tracks and intensity, Typhoon Ragasa traveled over the sea south of Macau and did not make landfall there, but it was considerably stronger than Typhoons Hato and Mangkhut. According to Fig. 6, residents appear to have perceived Typhoon Ragasa as the weakest; however, it is noteworthy that Ragasa was in fact the strongest of the three typhoons in terms of intensity. Although Typhoon Hato was the weakest of the three typhoons, it passed closest to Macau (Fig. 11), resulting in the strongest winds there and the most pronounced storm surge.

The delayed issuance of typhoon signals during Typhoon Hato can also be inferred from Fig. 11. Signal No. 10 was issued at the very moment the typhoon was making landfall, at which point it is evident that resident evacuation would have been difficult. The absence of respondents who evacuated at Signal No. 10 in Fig. 9 may be attributed to the severity of wind and rainfall, which likely prevented evacuation even among those who wished to do so. Signal No. 8 was issued only after the typhoon had approached within 100 km of Macau, which can be considered considerably late.

In contrast, for Typhoons Mangkhut and Ragasa, Signal No. 10 was issued when the typhoons were more than 100 km away from

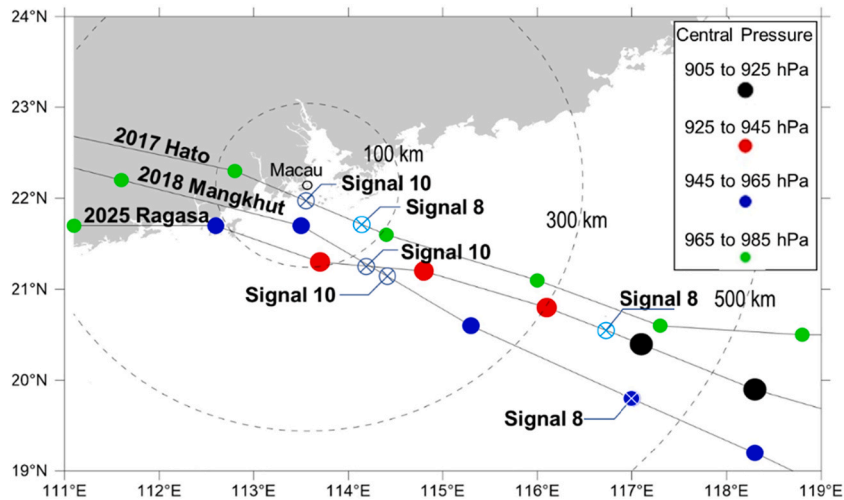


Fig. 11. The tracks of the three typhoons and the estimated typhoon centers at the time Signal No. 8 and 10 were issued in Macau. Data sources for typhoon tracks and intensity: JMA Best Track Data.

Macau, and Signal No. 8 was issued when they were approximately 300–500 km away, indicating that the signals were issued much earlier than in the case of Hato. The fact that the largest number of respondents evacuated at Signal No. 10 during Typhoon Ragasa in Fig. 9 is likely because the outdoor weather conditions were still not severe enough to prevent evacuation. This may also be related to Ragasa's track eventually passing about 90 km west-southwest of Macau rather than striking the city directly (Fig. 11). In addition, as shown in Fig. 12, Ragasa's forward speed was 18 km/h, which was approximately 40% slower than that of Hato (30 km/h) and Mangkhut (34 km/h). This slower movement is considered advantageous, as it provided more time for evacuation. As noted above, the issuance of Signal No. 8 and No. 10 for Typhoon Hato was overly tight in terms of timing; this may have been partly due to the relatively rapid translational speed of the typhoon, which resulted in limited time for crucial decision-making.

The low number of evacuations at Signal No. 10 during Typhoon Mangkhut is unclear, but many residents likely evacuated earlier at Signal No. 8 as a precaution, as Mangkhut occurred the year after the historically worst Typhoon Hato. Such disaster experiences, particularly those accompanied by psychological trauma, are more likely to heighten evacuation awareness than those without such trauma [15].

Table A1 shows that the typhoon signal criteria are primarily based on wind speed; however, in operational practice, additional meteorological factors are likely considered. Based on the present analysis, indicators such as the distance to the typhoon center and the predicted time of typhoon arrival could be quantitatively used alongside wind speed to support decision-making. Lessons from the warnings issued for Typhoons Mangkhut and Ragasa suggest that issuing Signal No. 8 when the typhoon center was still at a relatively large distance (e.g., 300–500 km) may represent an effective practice for future consideration.

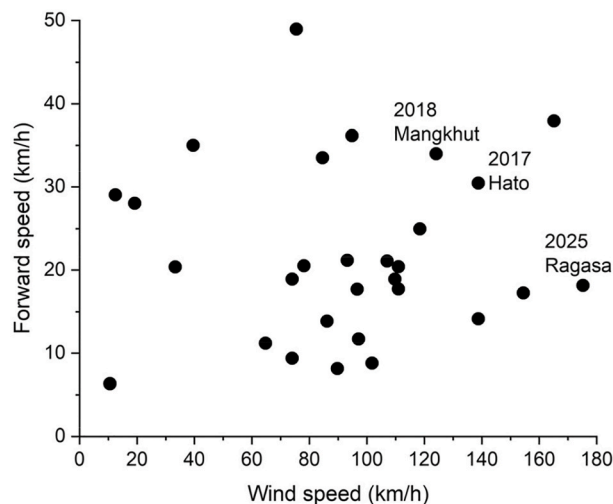


Fig. 12. Pre-landfall forward speed and maximum sustained wind speed of 29 typhoons approaching Macau (1977–2025).

4.2. Adaptive measures to enhance coastal resilience in Macau

The most significant change in Macau's administrative responses since Typhoon Hato in 2017 is the earlier issuance of typhoon signals and the more precautionary implementation of government messages and actions encouraging the evacuation of residents. However, our surveys also reveal a number of other improvements; therefore, this section introduces local responses aimed at enhancing typhoon resilience.

Fig. 13 shows the measures taken in various locations after Typhoon Hato in response to typhoons, particularly storm surges. Photos (a)–(d) show simple portable floodgates made of steel panels. While not installed at every house, several were observed at the entrances of shops. According to an employee of a shop, thanks to the installation of the floodgate and a drainage pump, their shop was able to minimize flood damage during Typhoon Ragasa, whereas other nearby shops without such installations suffered flooding. These measures are relatively low-cost while highly effective, and their adoption by many more individual households can be expected. However, as they are fundamentally private rather than government-led measures, some cost is involved. Users also need to verify the performance of the floodgates themselves. Potential issues include water leakage between panels, insufficient resistance to floodwater pressure that could cause the gate to fail suddenly and allow seawater to rush in, or the gate making it more difficult for residents to evacuate the house. These potential negative effects should be carefully considered.

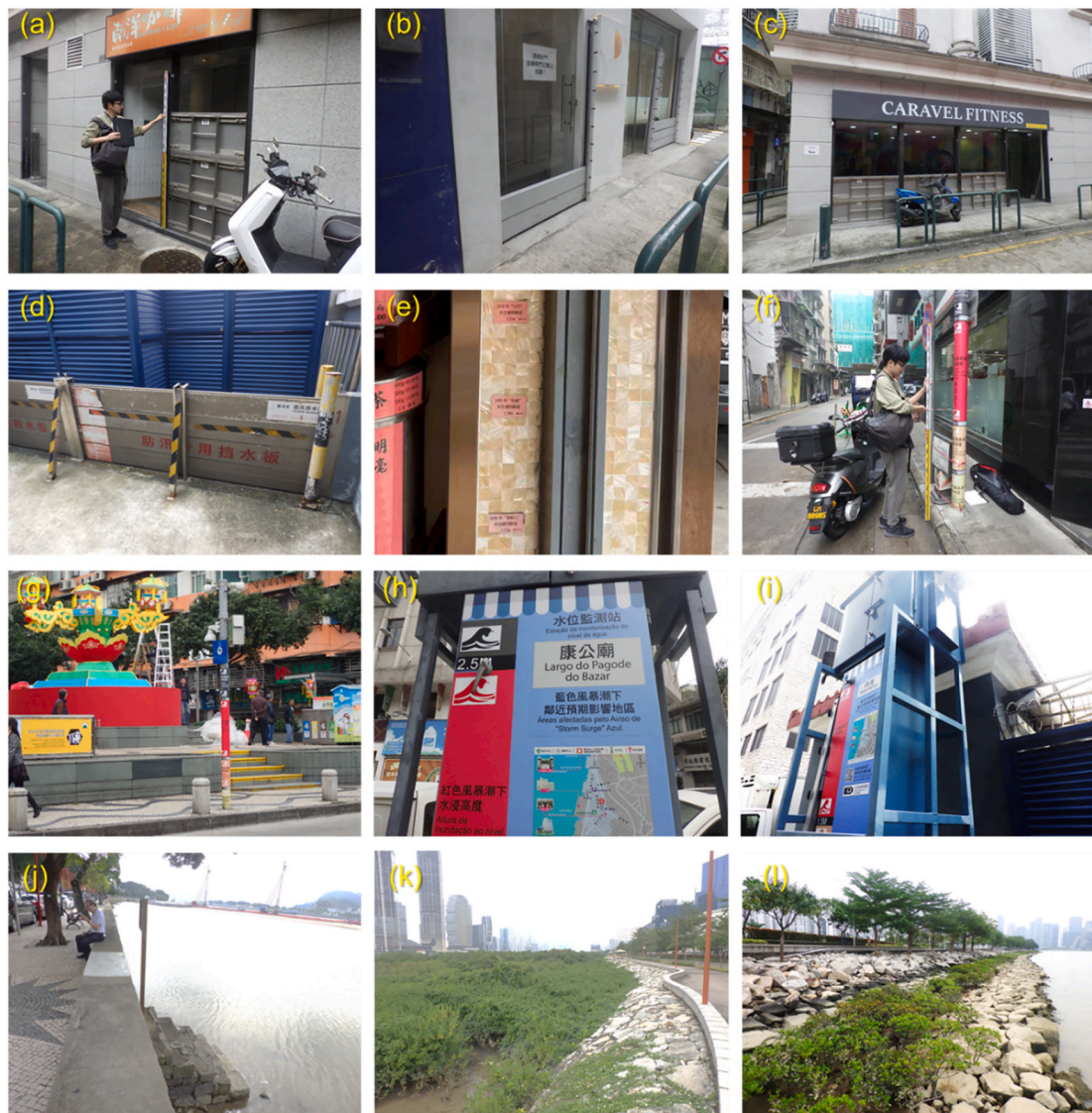


Fig. 13. (a) – (c) Manual floodgates installed at a shop entrance, (d) Manual floodgates installed in the Inner Harbour, (e) Past typhoon-induced inundation levels are recorded on the pillar, (f) – (g) A storm surge warning post, (h) – (i) Water level monitoring stations, (j) A coastal staircase with its entrance filled with concrete to block storm-surge intrusion, (k) and (l) Mangrove planting in front of the coastal revetment.

Photo (e) shows a shop where the owner has precisely recorded the flood depths from past storm surges on the pillars—2.14 m for Typhoon Hato, 1.51 m for Typhoon Mangkhut, and 1.36 m for Typhoon Becky in 1993—illustrating a high level of individual awareness regarding storm surges. In addition to this location, a considerable number of residents could recall the approximate height to which seawater had risen inside their homes during Typhoons Hato, Mangkhut, and Ragasa.

Photos (f) and (g) show posts indicating the predicted storm surge heights. As described in [Table A1](#), the posts are color-coded into five levels: blue, yellow, orange, red, and black. Additionally, speakers for broadcasting warning alerts are installed at the top of these posts. These posts were rapidly installed after Typhoon Hato, and by the time we conducted our survey following Typhoon Mangkhut in 2018, many of them were already in place. During Typhoon Ragasa, the second-highest red signal was issued, and we confirmed that inundation levels had indeed reached this range. The explanatory signage is provided in Chinese and Portuguese. In Macau, which receives many tourists, it would be beneficial to include English signage as well.

On the other hand, photos (h) and (i) depict water level observation facilities, which are similarly marked with color-coded storm surge levels. These water level monitoring systems are managed by the SMG, and currently, real-time inundation levels are publicly available at 11 locations, primarily within the Inner Harbour area.

Photos (j)–(l) show the situation in the Taipa–Coloane area, which is on a different island from the Inner Harbour district. During Typhoon Hato, parts of this area also experienced inundation due to the storm surge [17]. Seven years have passed since then, yet interestingly, the embankment heights remain unchanged. One minor difference is that during Typhoon Hato the stairs led down to the coast, but the entrance was later blocked with concrete, presumably to prevent seawater intrusion.

Photo (k) shows the mangroves in the Cotai area. Although they appear to be natural forest, these mangroves were actually transplanted from areas affected by reclamation and have since grown into a healthy stand [45]. It seems that the presence of the mangrove forest in this area allows for a lower height of the embankments, which can be seen as an example of implementing cutting-edge measures known as coastal nature-based solutions or hybrid solutions [46]. As this area is reclaimed land experiencing ongoing subsidence due to soil consolidation [47], which is expected to increase storm-surge risk, the expansion of mangrove forests is expected to help mitigate these impacts.

Photo (l) illustrates the recent mangrove afforestation in Taipa. As the mangroves are immature and narrow, they are not currently expected to mitigate storm surges effectively, but they will contribute to the establishment of a waterside habitat. Although residents did not suggest using mangroves as a measure ([Fig. 7 Q8](#)), mangroves are considered a promising solution in Macau.

#### 4.3. Disaster management implications for coastal cities exposed to storm surges

Typhoon Hato is regarded as a rapidly intensifying typhoon [17,44], as evidenced by the more abrupt changes in atmospheric pressure and wind speed compared with Mangkhut and Ragasa shown in [Fig. 8](#). Although modern tropical cyclone forecasting performs well under typical conditions—such as sufficiently warm sea surface temperatures and low vertical wind shear—it remains less reliable in predicting rapid intensification under unfavorable environmental conditions (Elsberry et al., 2025). Furthermore, the generation of significant storm surges depends not only on meteorological factors (e.g., atmospheric pressure, wind speed, and storm size) but also on topographic and geographical factors, including landfall location and approach speed, coastal geometry, and seabed depth and slope, which further complicates prediction [48,49]. Moreover, because storm surges and astronomical tides occur independently, predicting their combined effect—the “storm tide”—is even more challenging. These considerations indicate that typhoon and storm-surge warnings cannot rely solely on numerical forecasts.

Given the inherent limitations of current forecasting capabilities, warnings should be issued well in advance with sufficient lead time, taking into account the various meteorological, geographical, and modeling uncertainties involved. As shown in [Fig. 11](#), in the case of Typhoon Hato, Signal No. 8 and Signal No. 10 were issued only when the storm approached within 100 km of Macau. Even if this decision were appropriate based on wind speed criteria, it was too late when considering the time required for residents to evacuate. In contrast, for Ragasa, Signal No. 8 was issued when the typhoon was more than 300 km away, which can be evaluated as a timing that secured sufficient lead time to respond even to rapid changes in typhoon intensity.

False alarms may indeed trigger a “cry wolf” effect, potentially diminishing people's risk perception or sense of urgency. However, the occurrence of typhoons—particularly those capable of generating life-threatening storm surges—is far less frequent than that of other weather-related hazards such as heavy rainfall and strong winds. Although Macau has experienced storm surge damage three times over the past decade, such events remain relatively rare in most coastal cities. Moreover, the positive evaluation by residents of the authorities' response to Typhoon Ragasa underscores the importance of issuing early warnings as a fundamental principle of disaster risk management, even at the risk of premature alerts.

The fact that Macau's post-storm surge disaster countermeasures have focused primarily on non-structural (soft) measures will also be highly instructive for other coastal cities. This stands in contrast to regions such as Japan and the Netherlands, where a hard-infrastructure-oriented approach predominates, and disaster prevention is centered on structural measures, including determining the height and design of coastal dikes based on estimated storm-surge return periods. Although Macau has suffered storm surge damage from three recent typhoons, the impacts have been mainly economic, with relatively limited loss of life. This outcome can be attributed to the effectiveness of soft measures centered on evacuation guidance, together with the high standards of urban infrastructure, including housing.

## 5. Conclusion

In this study, we investigated three major typhoons in Macau—Typhoons Hato (2017), Mangkhut (2018), and Ragasa (2025)—to

examine changes in residents' evacuation behavior and government responses. Macau's experiences with storm-surge flooding from these typhoons have resulted in substantial improvements in coastal resilience in less than a decade. The most notable advancement has been the earlier issuance of typhoon signals, particularly the critical escalations to Signals No. 8 and No. 10, which provide residents with longer lead times for evacuation. Our survey results indicate that government warnings strongly influenced evacuation behavior, with many residents following official guidance, while social influence and prior disaster experience also shaped decisions. Despite Typhoon Ragasa potentially being the most intense of the three and causing flooding in the Inner Harbour area, respondents perceived it as less severe, likely reflecting improved preparedness and timely warnings. In addition to early typhoon signals, Macau has implemented multiple adaptive measures to mitigate storm-surge impacts. These include portable flood-prevention gates, real-time water level monitoring stations, color-coded storm surge posts, detailed individual records of past inundation levels, and mangrove afforestation as a nature-based hybrid solution. While major structural defenses such as high seawalls remain limited, these soft measures, combined with heightened public awareness and readiness, appear to have strengthened overall resilience. Macau's approach will be highly instructive for disaster prevention and management strategies in other coastal cities facing similar typhoon risks. Nevertheless, Macau is not yet fully resilient to future typhoons. A direct landfall by a very strong storm like Typhoon Ragasa would likely have caused far greater damage, underscoring the need for continued improvements. Ongoing investment in advanced early warning systems, risk communication, public education, hybrid solutions, and incremental adaptive measures will be essential for coping with stronger typhoons and sustaining long-term coastal resilience in a city that holds one of the highest concentrations of wealth in the world while being directly exposed to the open ocean.

### CRedit authorship contribution statement

**Hiroshi Takagi:** Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yuzhe Zhao:** Resources, Investigation, Data curation.

### 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

**Table A1**

Summary of Tropical Cyclone and Storm Surge Signals in Macau (Based on publicly available information from the Macao Meteorological and Geophysical Bureau (SMG))

Typhoon Signal	Interpretation of Warning Signals	Safety Precautions	Storm Surge Signal	Interpretation of Warning Signals
Signal 1	Precaution Signal: A tropical cyclone is located within 800 km of Macau and may affect the city.	Take preventive measures, secure loose objects and construction materials, reinforce structures, clear drains, and ensure vessels seek safe shelter.	Blue	The water level is expected to remain below 0.5 m above road level.
Signal 3	Under the influence of a tropical cyclone, sustained winds of 41–62 km/h (11.4–17.2 m/s) are expected or already occurring in Macau, with gusts potentially exceeding 110 km/h (30.6 m/s).	Take preventive measures, secure property and vessels, monitor warnings, adjust activities, and stay cautious outdoors and on roads.	Yellow	The water level is expected to rise 0.5 to 1.0 m above road level.
Signal 8	The tropical cyclone continues to approach Macau. Sustained winds of 63–117 km/h (17.5–32.5 m/s) are expected or already occurring, with gusts possibly exceeding 180 km/h (50 m/s).	Complete preventive measures, stay indoors and away from windows, suspend schools and outdoor/marine activities, monitor tropical cyclone and storm surge warnings, and be alert for changing wind directions and bridge closures.	Orange	The water level is expected to rise 1.0 to 1.5 m above road level.
Signal 9	The tropical cyclone is moving closer to Macau. Sustained winds of 63–117 km/h (17.5–32.5 m/s) are blowing and are expected to intensify significantly.	Stay indoors and away from windows, suspend outdoor and marine activities, remain alert to sudden changes in winds, and closely monitor tropical cyclone and storm surge warnings.	Red	The water level is expected to rise 1.5 to 2.5 m above road level.
Signal 10	The center of the tropical cyclone will strike Macau imminently. Sustained winds exceeding 118 km/h (32.8 m/s) are expected or already occurring, accompanied by very strong gusts.		Black	The water level is expected to rise more than 2.5 m above road level.

Note on spelling: In this study, the official spelling 'Macao' is retained for proper nouns (e.g., The Macao Meteorological and Geophysical Bureau), whereas 'Macau' is used for all other references to the region.

**Table A2**

Results of the questionnaire survey, based on interviews with 94 residents conducted in January 2019.  
Respondent attributes: 43 male and 51 female (Data from Ref. [24])

Questionnaire items	%	
<b>Age:</b>		
➢ 19	6	
➢ 20 to 29	37	
➢ 30 to 39	26	
➢ 40 to 49	11	
➢ 50 to 59	9	
➢ over 60	12	
<b>Which was stronger, Typhoon Hato in 2017 or Mangkhut in 2018?</b>		
➢ 2017 Hato	85	
➢ 2018 Mangkhut	5	
➢ similar	9	
➢ I don't know	1	
<b>Do you feel that the government's response improved after Hato?</b>		
➢ Yes, but slightly	22	
➢ Yes	21	
➢ Yes, quite a lot	45	
➢ Not sure	10	
➢ No	2	
<b>Where did you evacuate to during the typhoon?</b>		
	Hato	Mangkhut
➢ A hill/higher ground	6	7
➢ An upper floor of your house	57	63
➢ A neighboring building	1	3
➢ An official evacuation facility	4	3
➢ I did not evacuate	25	12
➢ Other	1	5
<b>Which typhoon signal was in effect when you evacuated?</b>		
	Hato	Mangkhut
➢ Signal 1	0	1
➢ Signal 3	12	9
➢ Signal 8	57	69
➢ Signal 9	1	0
➢ Signal 10	2	2
➢ I don't remember	5	3
<b>What was your reason for evacuating?</b>		
	Hato	Mangkhut
➢ Strong wind	8	8
➢ Storm surge	25	24
➢ Heavy rain	2	0
➢ Warning from family or neighbors	5	3
➢ Warning from TV or radio	33	46
➢ Warning from social media (SNS)	7	6
➢ Public loudspeaker/community announcement	3	8
➢ Other	0	0
<b>What was your reason for not evacuating?</b>		
	Hato	Mangkhut
➢ I did not feel in danger	2	7
➢ No evacuation order issued	9	2
➢ I did not know where to evacuate	1	0
➢ Nobody around evacuated	0	0
➢ Weather conditions too severe to go outside	5	3
➢ I felt safer staying inside the house	18	16
➢ Other	1	0
<b>Do you think the government's response was timely?</b>		
	Hato	Mangkhut
➢ Timely	12	86
➢ Late	67	0
➢ Not sure	9	7
➢ Other	6	0
<b>What countermeasures would you like the government to implement?</b>		
➢ Higher and stronger dykes	27	
➢ River mouth flood gates	29	
➢ Raising the land/land elevation	4	

(continued on next page)

Table A2 (continued)

Questionnaire items	%
>Relocation to a safer place	2
>Mangrove plantation/restoration	1
>Evacuation buildings and towers	6
>Advanced weather forecasting	18
>Advanced warning systems	33
>Education programs and disaster drills	9
>I do not wish for any	8
>Other	17

## Data availability

Data will be made available on request.

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