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Operational Numerical Predictions, GNSS-IR Observation, and Post-Hazard Survey on Storm Surge in Macao under Super Typhoon Ragasa

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- Operational Numerical Forecast
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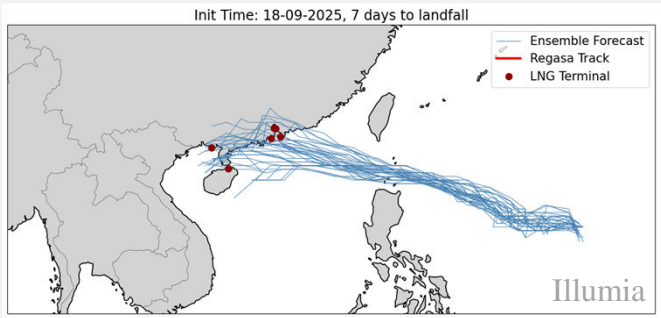
Super Typhoon Ragasa (2518)

Ragasa 2518, Super Typhoon, Northwest Pacific

- Generated in mid-Sept and named on 18 Sept;
- Landing in Yangjiang in the afternoon of Sept as STY and further in Beihai in the early morning of 25 Sept as STS and further in Fangchenggang;
- **Peak intensity**: Max. sustained winds (2-min): **62 m/s**; Mini. central pressure: **910 hPa**; (CMA)
- **Size** (NW/SW/SE/NE): $R_{13.9}$: 180/300/350/250 km; $R_{24.5}$: 120/150/100/100 km; $R_{32.7}$: 90/90/80/80 km; (CMA, nearest to Macao)
- **Impact on Macao**
  - ✓ Tropical Cyclone Warning Signal: **No. 10** (**10.5 h, longest since 1968**);
  - ✓ Storm Surge Warning Level: Fourth/**Red**;
  - ✓ Nearest SW 90 km around 11 a.m. 24 Sept;
  - ✓ Maximum wind speed of 52 m/s (CMA);
  - ✓ Mini MSLP: 982 hPa;
  - ✓ Max 10-min-mean wind: 36.2 m/s;
  - ✓ Max water level (surge): **4.61 (0.86) m**;
  - ✓ Max flooding depth: **1.51 m**;



“Five Suspension”

Class

Work

Production

Transportation

Business

> 14 cities

Storm Surge Flooding in Macao

❑ **Frequency of storm surge flooding in Macao is increasing**

Date	Maximum tidal level in Macao (m)	Maximum flooding depth in Macao (m)	Tropical cyclones
23/08/2017	5.58	2.38	Hato (1713)
16/09/2018	5.21	2.01	Mangkhut (1822)
17/09/1993	4.78	1.58 ← Ragasa (2518)	Becky (9316)
24/09/2008	4.63 ← Ragasa (2518)	1.43	Hagupit (0814)
15/09/2009	4.25	1.15	Koppu (0915)
18/07/1989	4.18	0.98	Gordon (8908)
24/07/2012	4.12	1.04	Vicente (1208)
19/08/2020	4.06	0.82	Higos (2007)
24/07/2003	4.00	0.80	Imbudo (0307)
13/10/1974	3.98	0.78	Bess
16/09/2014	3.94	0.81	Kalmaegi (1415)
24/07/1991	3.92	0.72	Brendan (9108)
13/10/2021	3.84	0.43	Kompasu (2118)
02/07/2022	3.83	0.50	Chaba (2203)
25/08/2022	3.81	0.22	Ma-on (2209)

Records of storm surge flooding in Macao

Storm Surge Flooding in Macao

❑ Comparison with Hato (1713) and Mangkhut (1822)

Item	Hato (1713)	Mangkhut (1822)	Ragasa (2518)
Lifetime max. intensity on the Saffir-Simpson hurricane wind scale	Category 3 08/23 9:00-13:00	Category 5 09/11 14:00 09/15 05:00-08:00	Category 5 09/21 8:00-17:00 09/22 17:00-09/24 13:00
Max. 2-min sustained winds speed (CMA)	52 m/s	65 m/s	62 m/s
Min. central Pressure (CMA)	935 hPa	910 hPa	910 hPa
Max. 10-min sustained wind speed in Macao (SMG)	35.5 m/s	35.0 m/s	36.2 m/s
Radius of Level-12 wind near Macao	60-80 km	60-120 km	80-90 km
Astronomical tide level at landfall	High tide level	Relatively low tide level	High tide level
Closest distance to Macao	About 30 km of SW	About 70 km of SW	About 100 km of SW
Forward speed at closest approach to Macao (CMA)	30 km/h 08/23 12:00	33 km/h 09/16 14:00	20 km/h 09/24 10:00
Min. atmos. pressure in Macao (SMG)	945.4 hPa	956.4 hPa	969.6 hPa
Max. storm tides above the Macao Chart Datum (SMG)	5.58 m (A-Ma gauge)*	5.21 m (SDV gauge)*	4.67 m (A-Ma gauge)
Max. inundation depth in Macao Inner Harbor (SMG)	2.38 m	2.01 m	1.51 m
Toll and damage in Macao	10 fatalities, 244 injured (DESPDR, 2017)	0 fatality, 40 injured (SMG, 2018)	0 fatality, 8 injured (SPU, 2025)

* Due to power outage or failure of monitoring instruments, these values were those recorded during the storms but maybe not the true peak.

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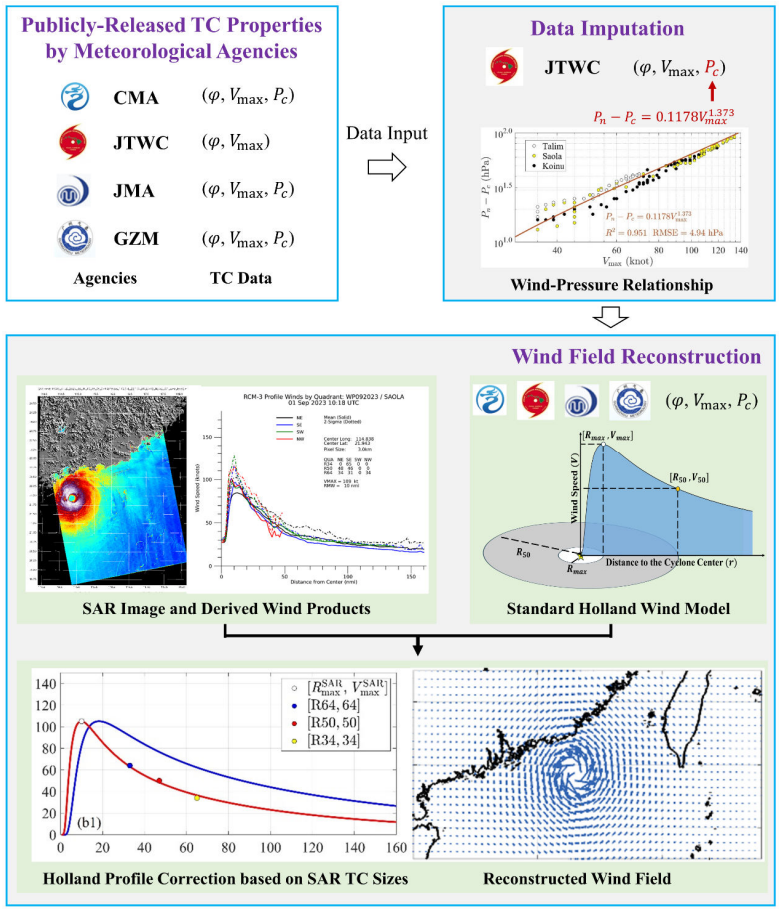
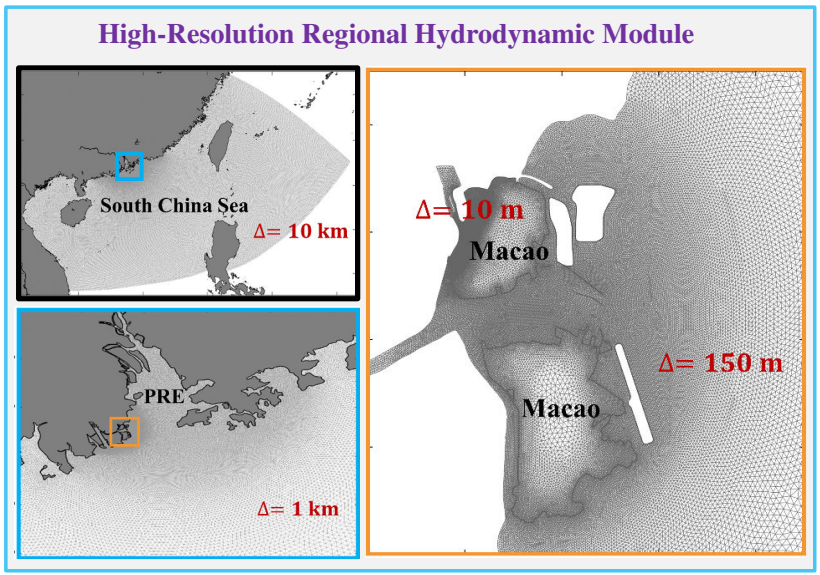
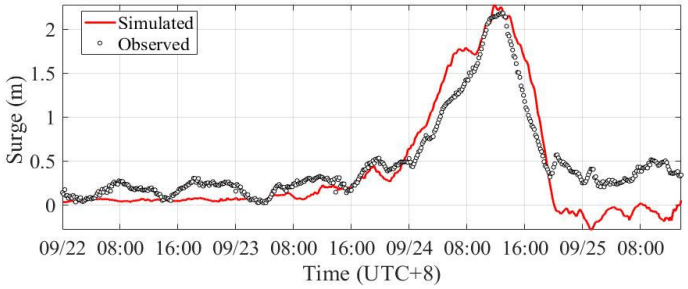
Operational Numerical Forecast

❑ A Storm Surge Operational Forecast Model based on Publicly-Released Meteorological Data



Wind Input





Output ⇧ (Water Level & Surge Height)

- Based on **publicly-released** meteor. data (track, V_{max}, P_c);
- Data from multi agencies for ensemble operational forecasts;
- A new **power** wind-pressure relationship (WPR) for data imputation;
- SAR-informed wind field correction;

Operational Numerical Forecast

❑ SAR-Informed Correction of Holland Wind Model

➢ Radius of maximum wind $R_{\max}$

$$R_{\max} = R_{\max}^{\mathrm{SAR}} = c_1 \cdot 51.6 \exp(-0.0223 V_{\max} + 0.0281\varphi)$$

➢ Holland parameter B

$$B = \frac{(V_{\max} - R_{\max}^{\mathrm{SAR}} f) V_{\max} \rho_a e}{P_n - P_c}$$

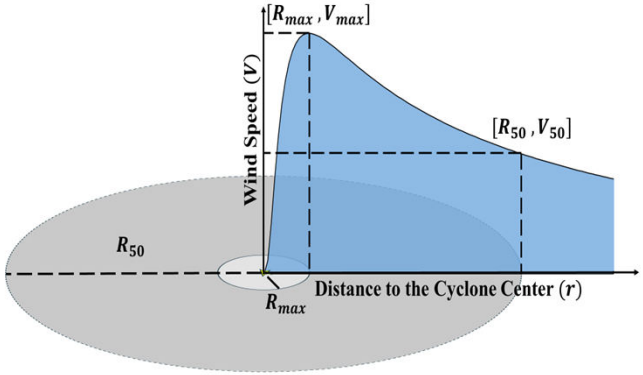
➢ Fitting-corrected wind field

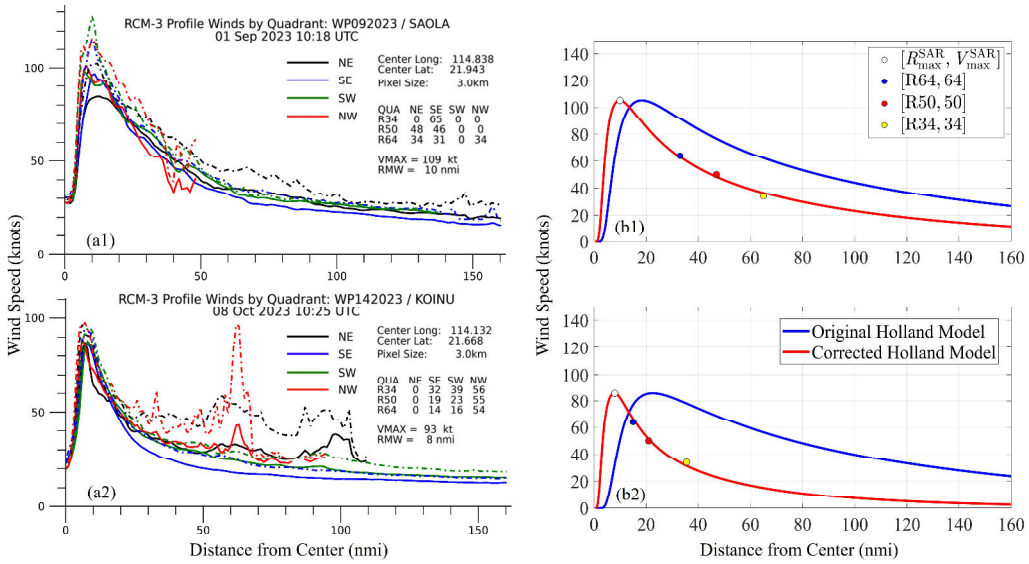
$$V(r) = c_2 \sqrt{\frac{c_3 B}{\rho_a}\left(\frac{R_{\max}^{\mathrm{SAR}}}{r}\right)^{c_3 B}(P_n - P_c)\exp\left[-\left(\frac{R_{\max}^{\mathrm{SAR}}}{r}\right)^{c_3 B}\right] + \left(\frac{f}{2}r\right)^2} - \frac{f}{2}r$$

➢ Air pressure

$$P(r) = P_c + (P_n - P_c)\exp\left[-\left(\frac{R_{\max}^{\mathrm{SAR}}}{r}\right)^{c_3 B}\right]$$

V_{max} maximum wind speed;
P_c pressure at TC center;
B Holland parameter;
$R_{\max}$ radius of maximum wind speed;
r distance from TC center;
f the Coriolis parameter;
$P(r)$ air pressure at r;
$V(r)$ wind speed at r;
φ latitude of TC center;
P_n central pressure; ρ_a air density.





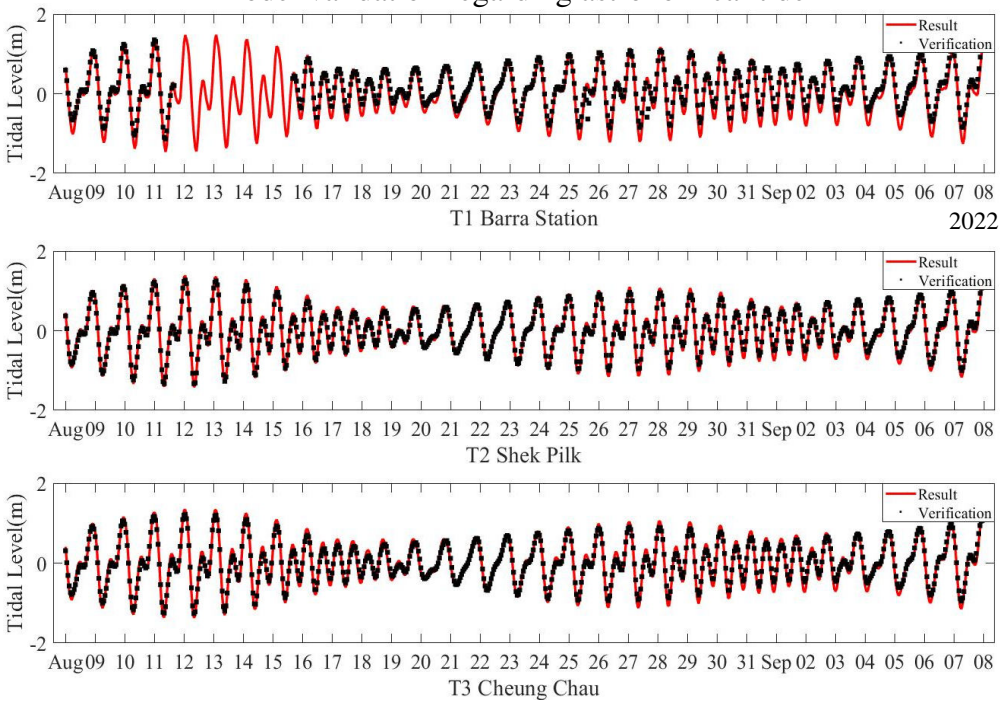
Operational Numerical Forecast

❑ Street-Scale FVCOM Hydrodynamic Module

- ➢ High spatial resolution: smallest grid of 10 m in the Inner Harbor region of Macao;
- ➢ A wide computational domain but focusing on Macao;
- ➢ Wet-dry boundary condition for intertidal zone;
- ➢ Tide-surge interaction accounted for;

Parameters	Setting
Domain	105.5°E-131.5°E, 13.5°N-28.75°N
Resolution	10 m ~ 10 km
Nodes & Cells	Nodes：123886, Cells：242178
Tide	M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, MN4
Prediction Cost	less than 15 min for 5-day 2D forecast (500 CPU cores)

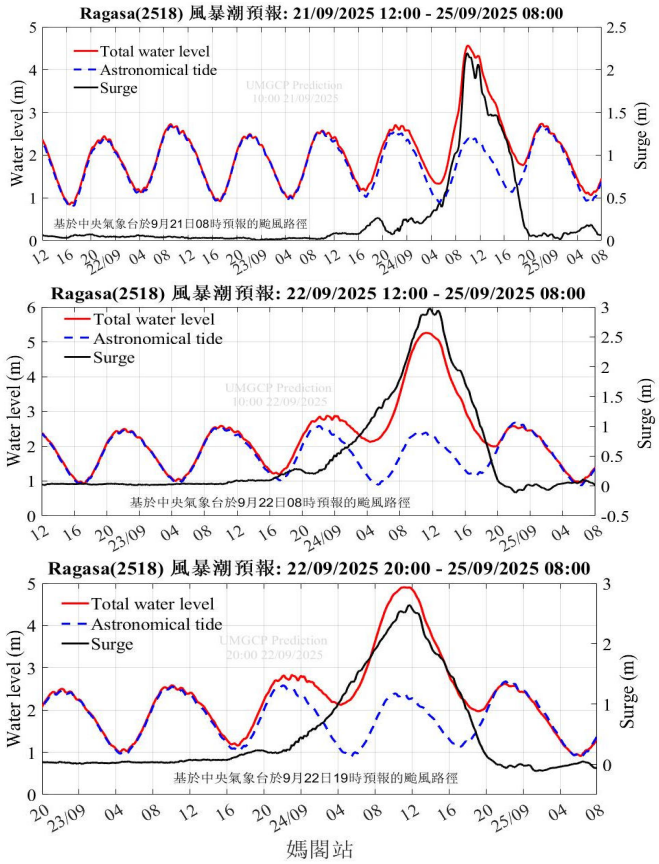
Model validation regarding astronomical tide



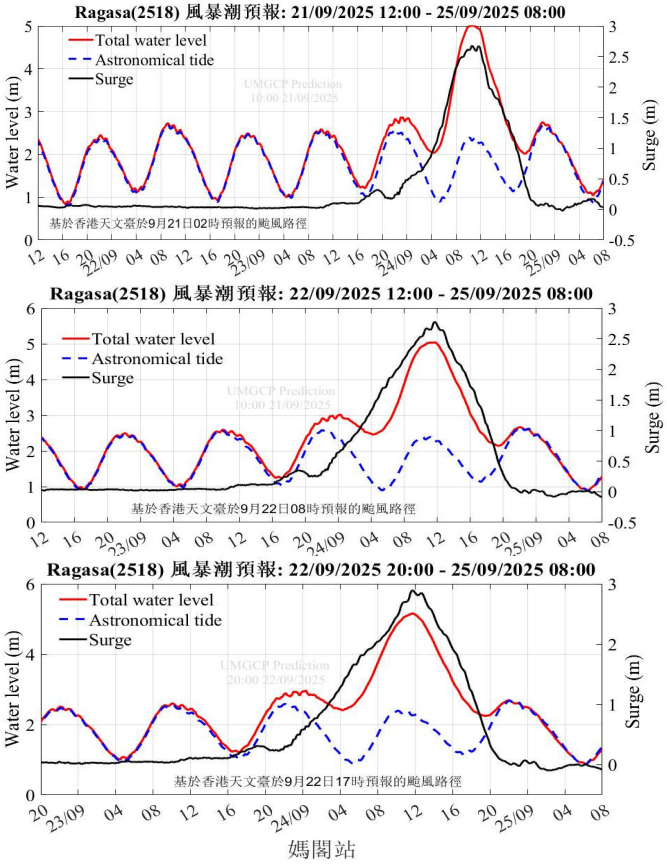
Tidal station	RMSE	Bias	R^2	Skill
Barra Station	0.1823	-0.1173	0.9762	0.9741
Shek Pilk	0.1152	0.0206	0.9836	0.9882
Cheung Chau	0.1054	-0.0274	0.9861	0.9907

Operational Numerical Forecast

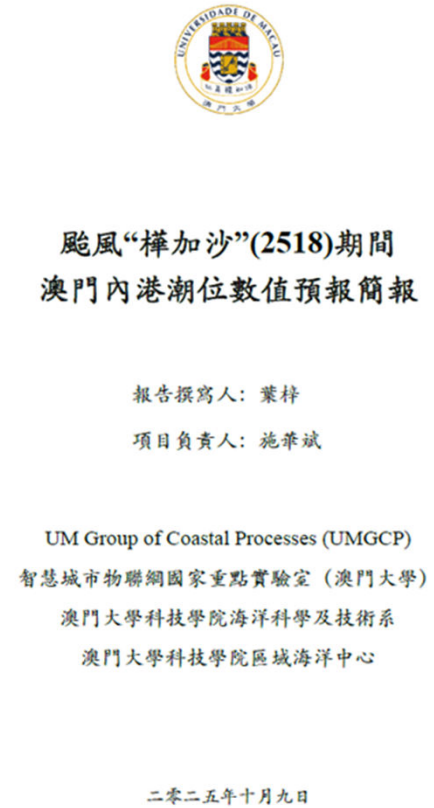
❑ Operational Forecast Products for Ragasa



Series forecasts based on national CMA data



Series forecasts based on regional HKO data



Forecast summary report for Ragasa

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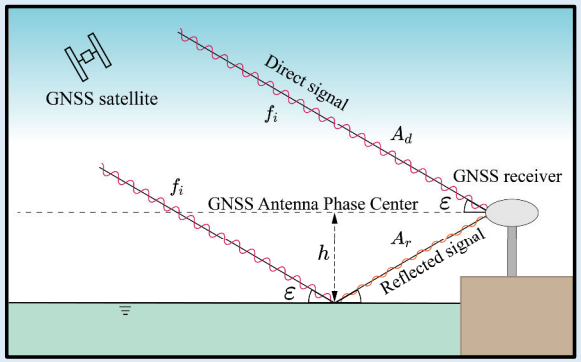
GNSS-IR Monitoring of Water Level

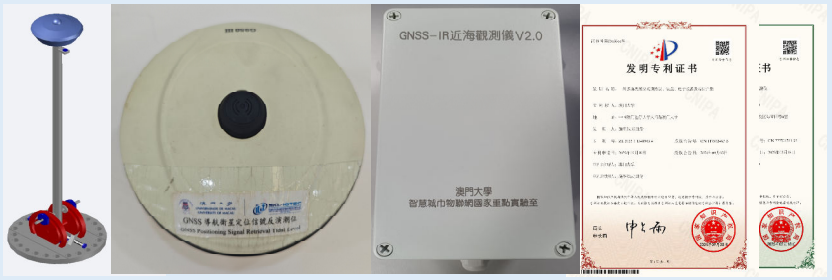
❑ GNSS-IR Observation Network for Coastal Hydrodynamics in Macao

GNSS-IR Altimetry Principle:

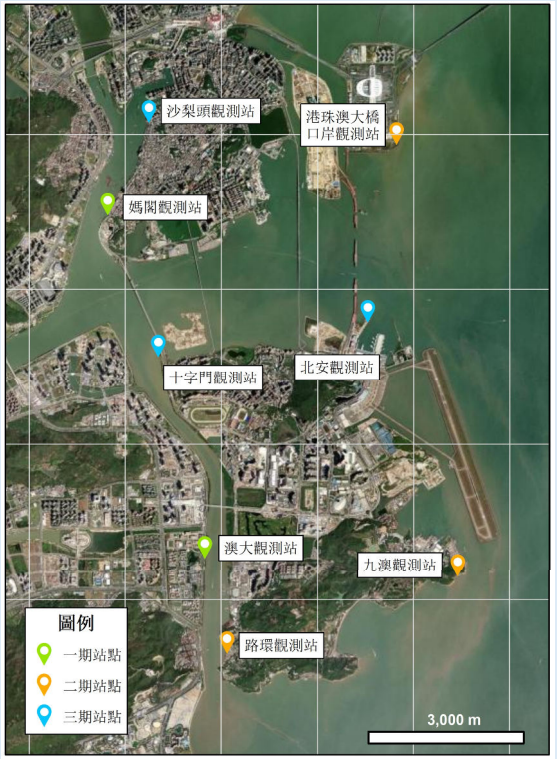
- ✓ GNSS receiver can receive both direct GNSS signals and those reflected from the water surface;
- ✓ Reflected signals interfere with direct signals, generating multipath effects that cause SNR (Signal-to-Noise Ratio) data to oscillate;
- ✓ Using spectrum analysis, we can obtain the reflector height from the SNR oscillation info.



Equipment development

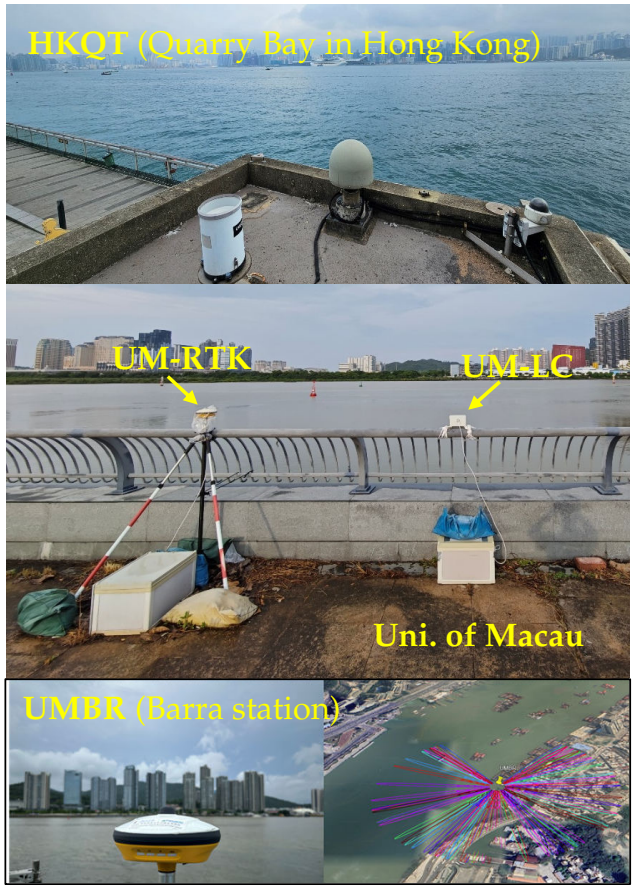


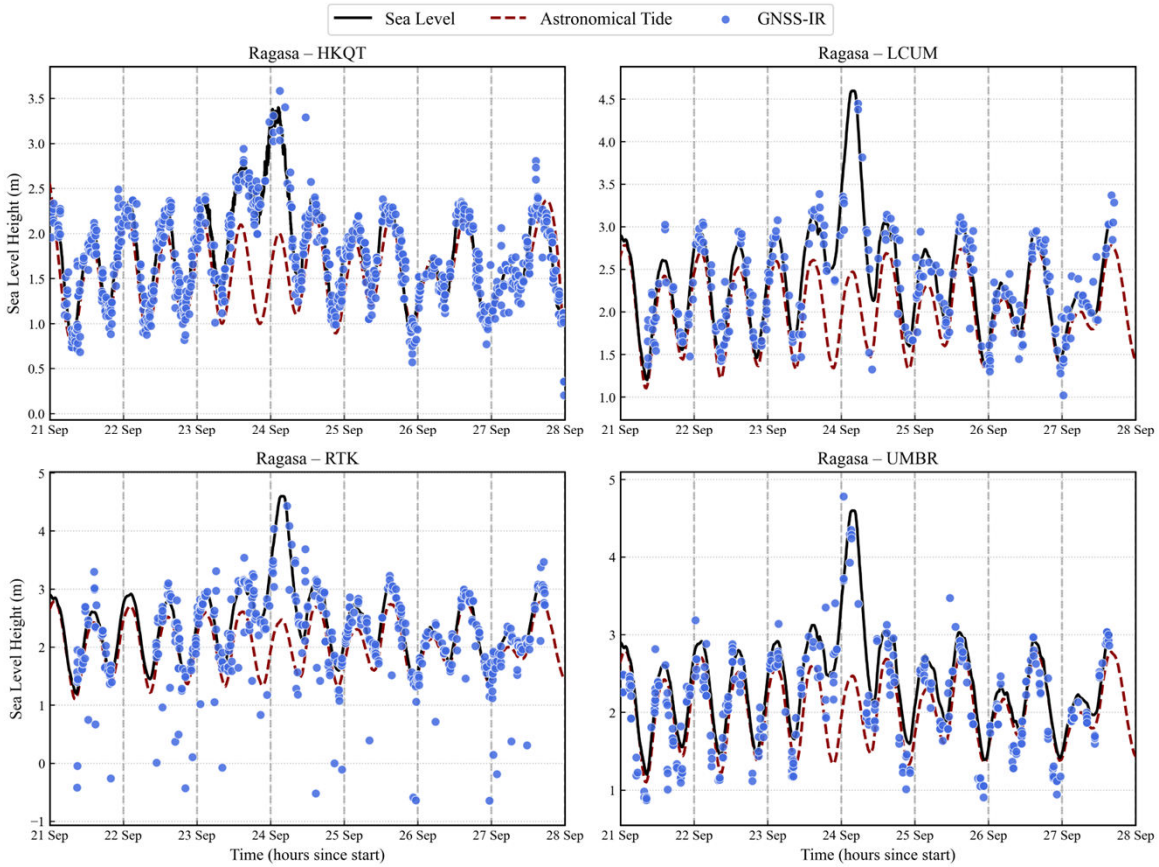
GNSS-IR Observation Network



GNSS-IR Monitoring of Water Level

❑ GNSS-IR Observation Network for Coastal Hydrodynamics in Macao





GNSS-IR observations of sea surface elevation during Ragasa (2518)

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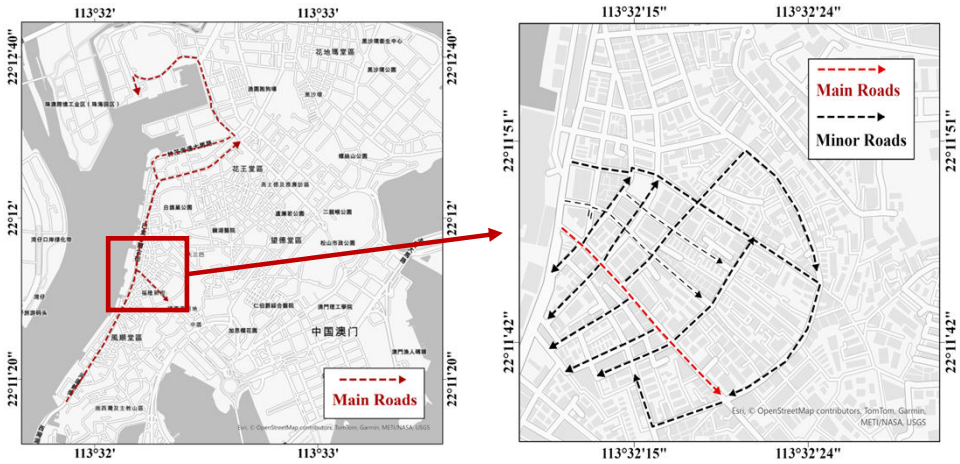
Post-Hazard Survey and Hindcast

❑ Post-Hazard Field Survey Plan

First-assessment based on municipal traffic information system



Survey Route Planning

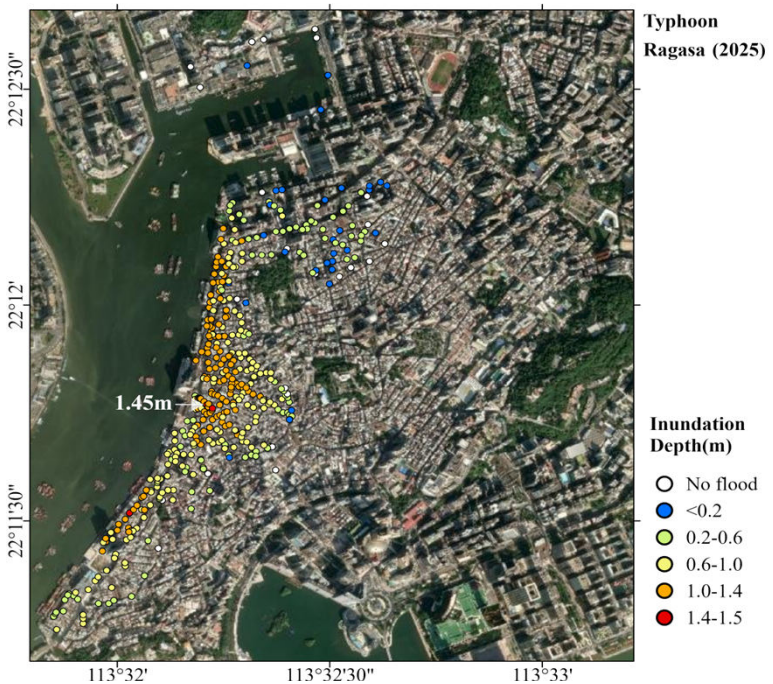
- **Inundation boundaries**: public surveillance footage
- **Specific Areas**: **all roads**
- **Launched**: **one** day after the typhoon
- **Lasted**: **three** days

Post-Hazard Survey and Hindcast

❑ Post-Hazard Field Survey Plan

Representative water marks

Resident Survey

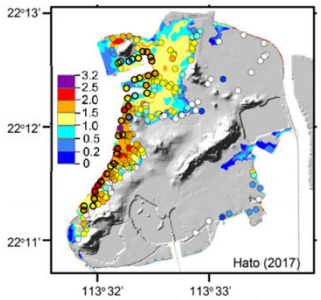


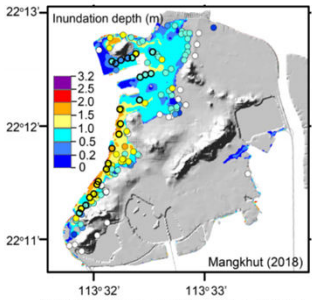
Results of field survey – Inundation depth

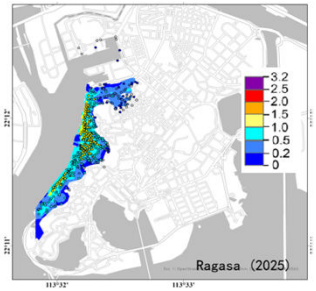
- **Quality Control**: GPS, Triple-measurements averaged, Dual-backup strategy
- **Result**: **431** survey points (54 resident report & 377 water marks) for a **high-resolution (20-25 m)** inundation map

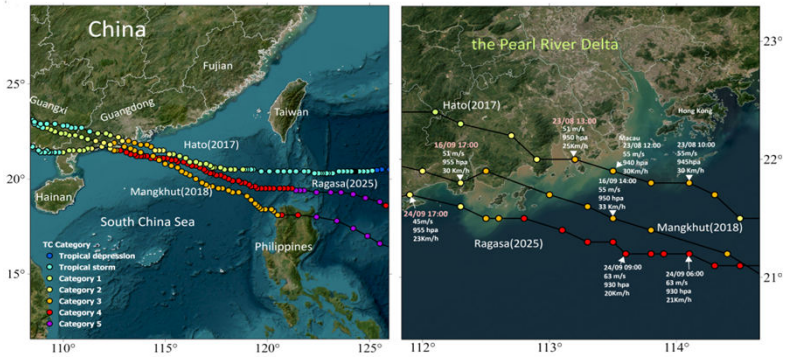
Post-Hazard Survey and Hindcast

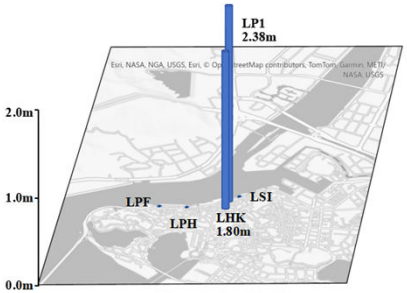
❑ Maximum Inundation Depth and Duration Comparison with Hato and Mangkhut

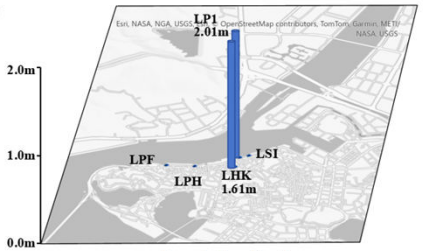


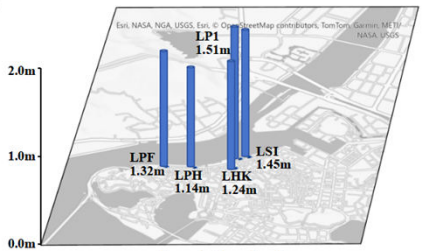


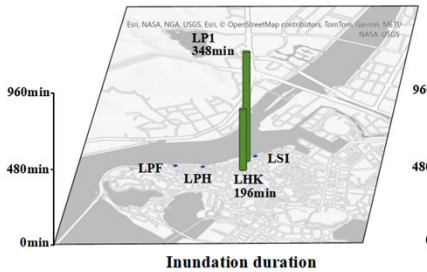


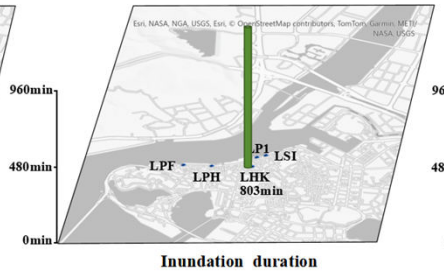


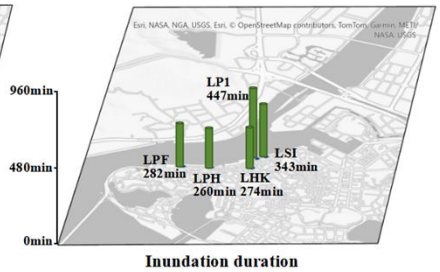








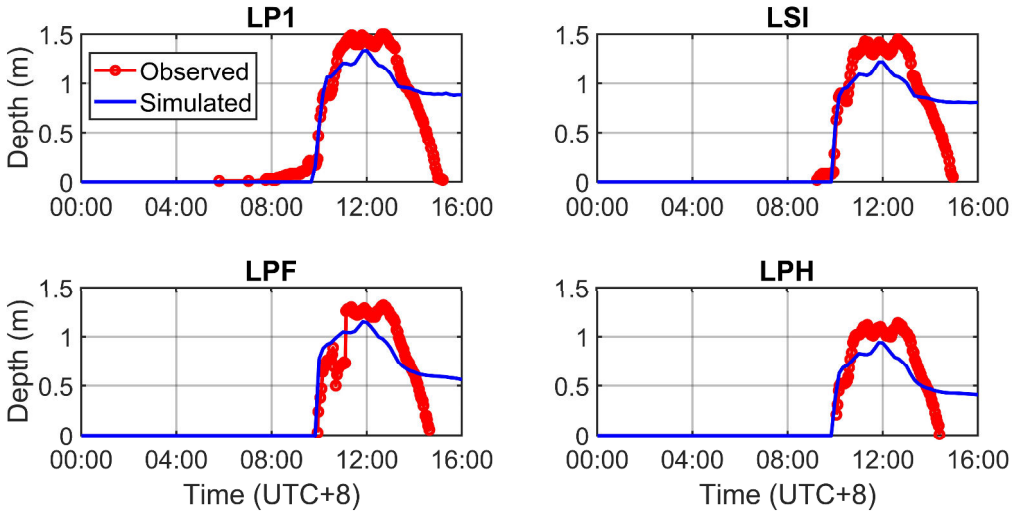




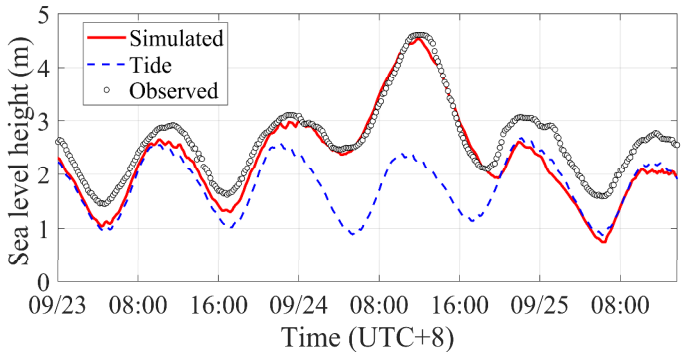
Scenario	Key Characteristics
Hato (1713)	High-Intensity, Short-Lived Nearest distance Macao in the core wind field Fast translation speed concentrated energy release
Mangkhut (1822)	Most severe overall impact Intermediate distance Immense wind radius Prolonged wind forcing and massive water volume
Ragasa (2518)	Most Intense, Moderate Impact Farthest distance Slow movement speed (20 km/h) but far Limited severity

Post-Hazard Survey and Hindcast

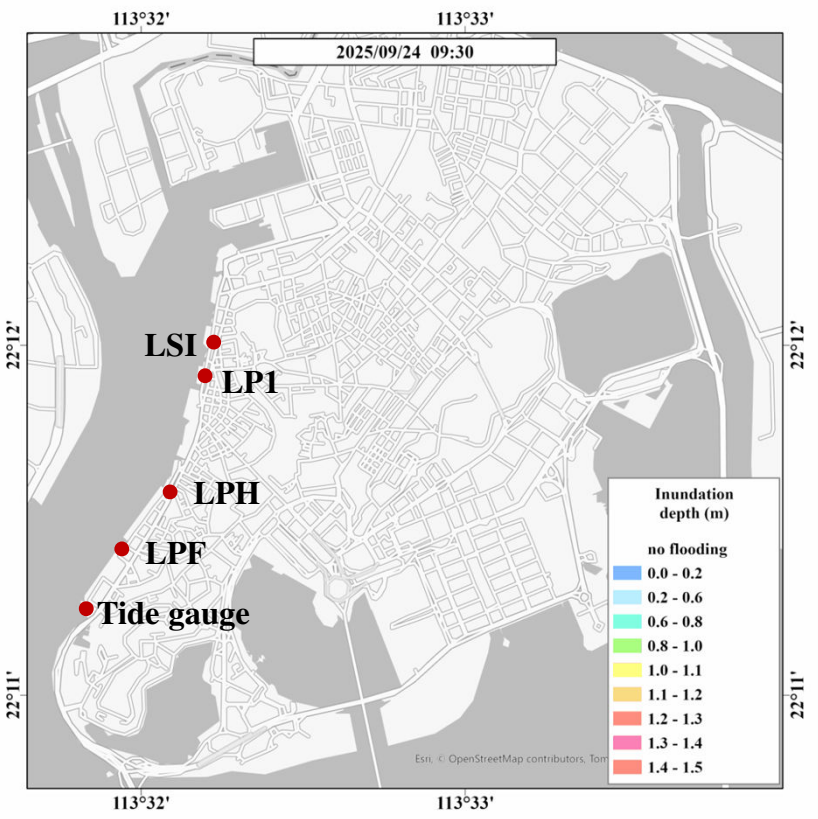
❑ Numerical Hindcast



(a) Comparisons between computed and observed water depth at water level stations



(b) Comparisons between computed and observed sea surface elevation at tide gauge of Macao



(c) Simulation inundation process in Macao induced by Ragasa (2518)

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