International Symposium on Grids & Clouds (ISGC) 2025

Hybrid Quantum Computing Workshop - I
15:00 - 15:30

Numerical Tool Development and Application for Surge-Tide-Wave Modeling

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京都大学

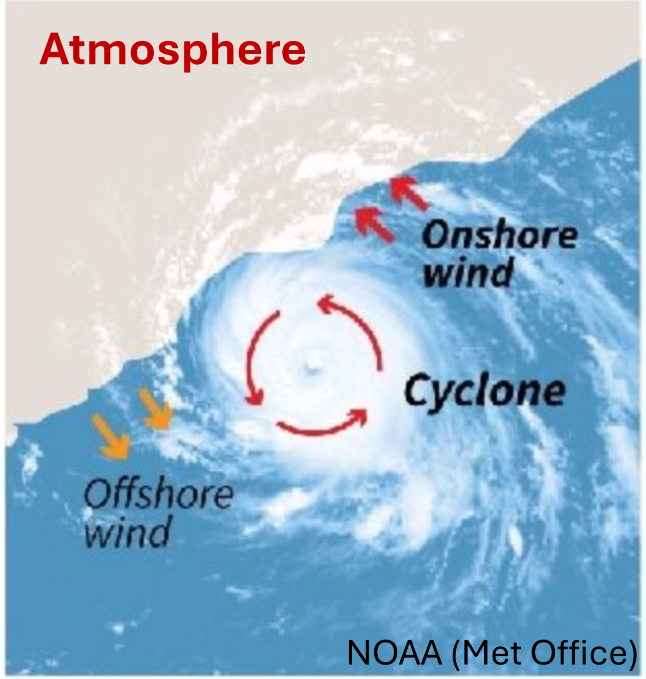
KYOTO UNIVERSITY

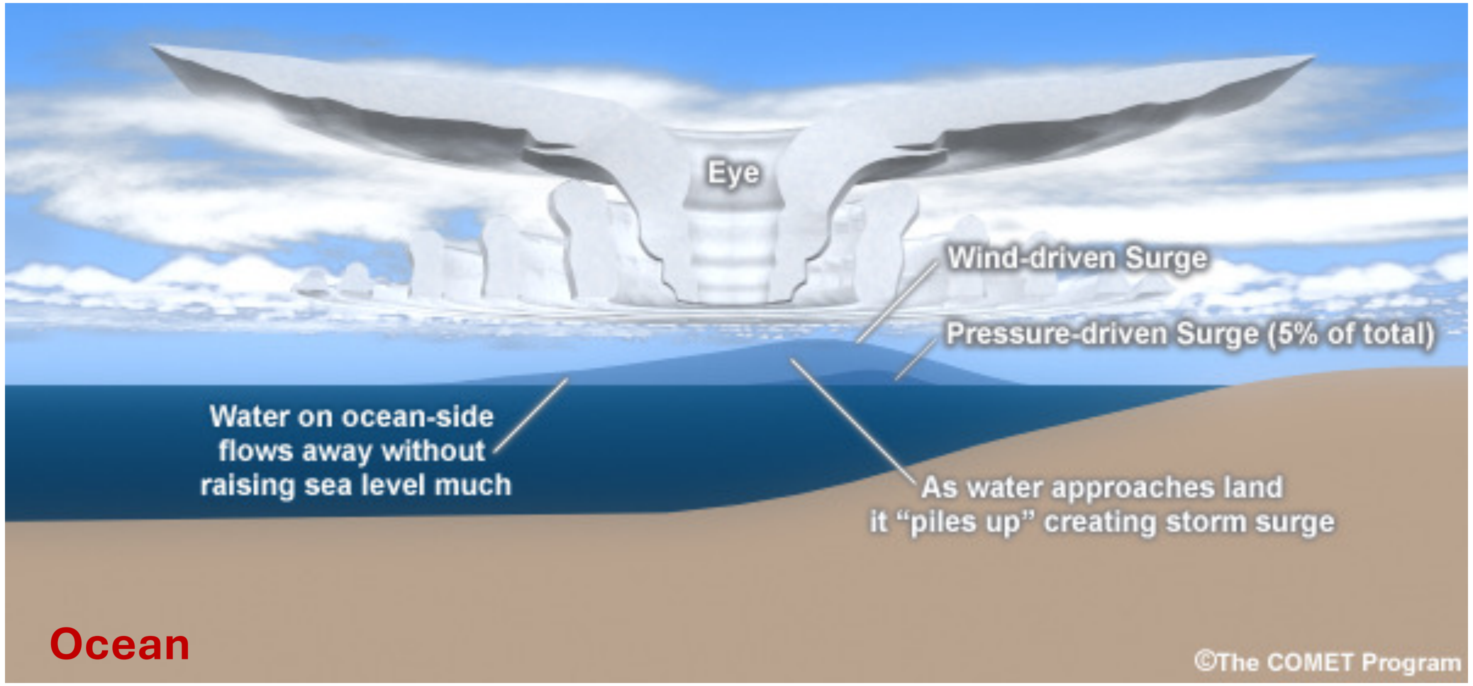
Storm Surge

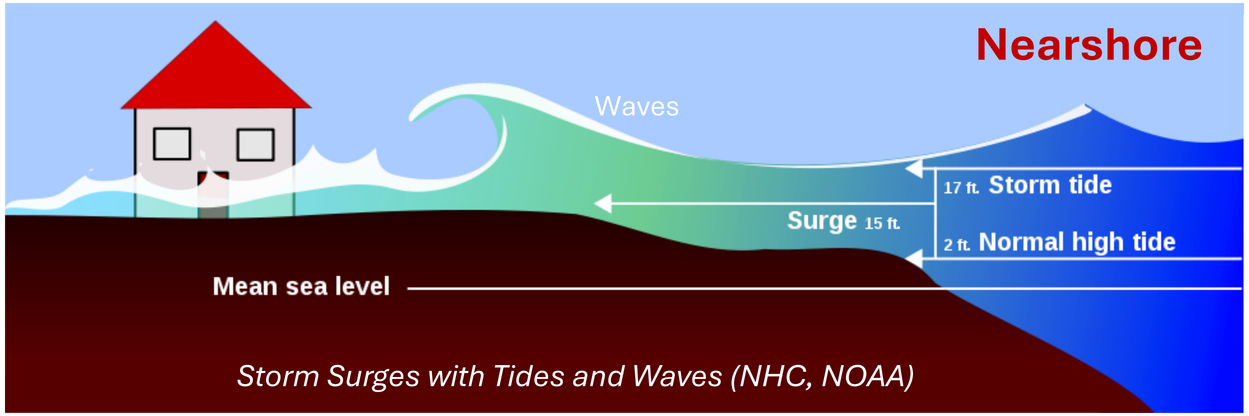
Storm surge, a meteorological forced long wave motion due to a tropical storm, is in a length scale of $O(10^2)$ *km* and a time scale of $O(10^0)$ to $O(10^1)$ *hr* (Bode and Hardy, 1997).

Multi-Scale Problem

Atmosphere
↓
Ocean
↓
Nearshore

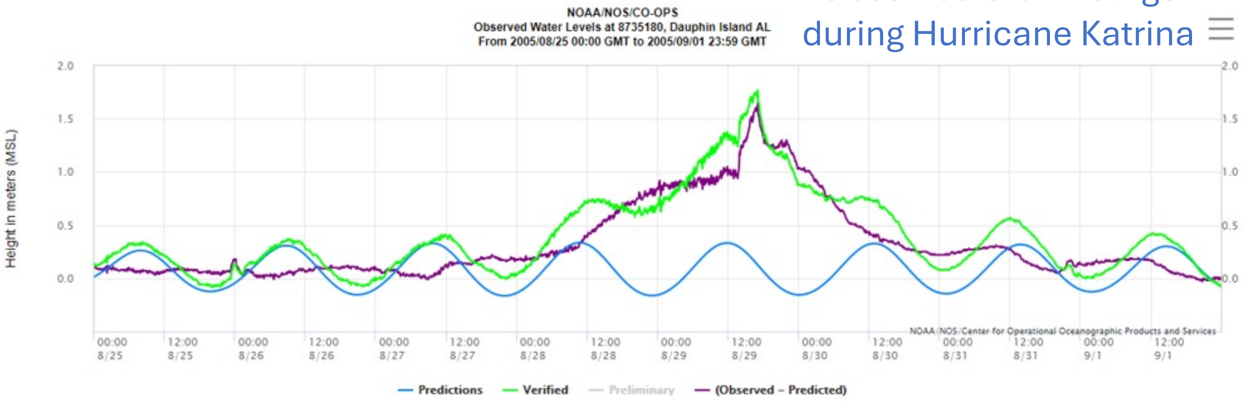






Storm Surges with Tides and Waves (NHC, NOAA)

Observed Storm Surge during Hurricane Katrina




IMPACT
BBC NEWS

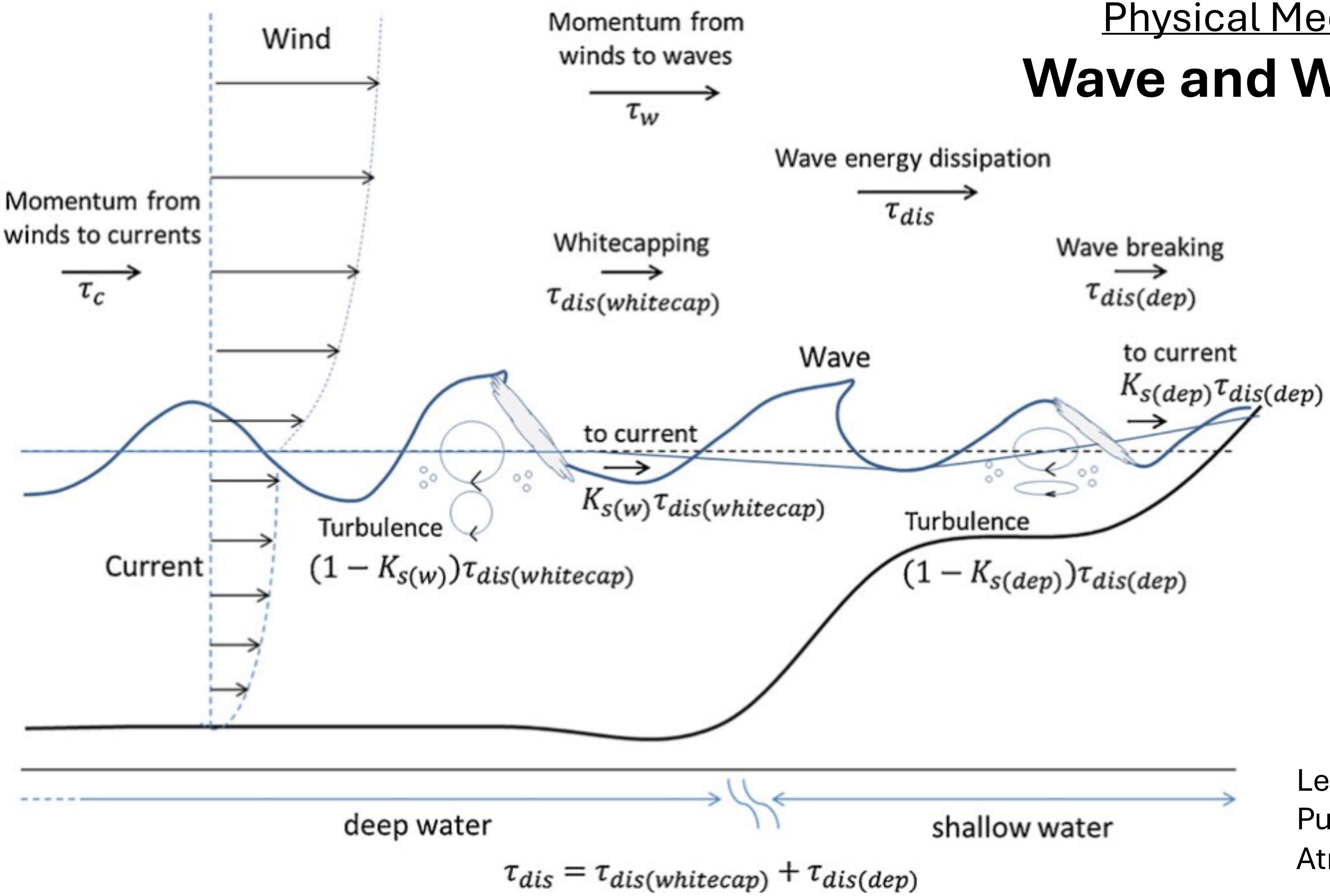
Storm Surge due to **Typhoon Haiyan (2013)** in the Philippines (Roeber & Bricker, 2015; Nature Communications)

Kansai Airport Inundated by Storm Surges due to Typhoon Jebi (2018)

Image credit: Kentaro Ikushima/Mainichi Newspaper via AP

<u>Physical Mechanism (1)</u>

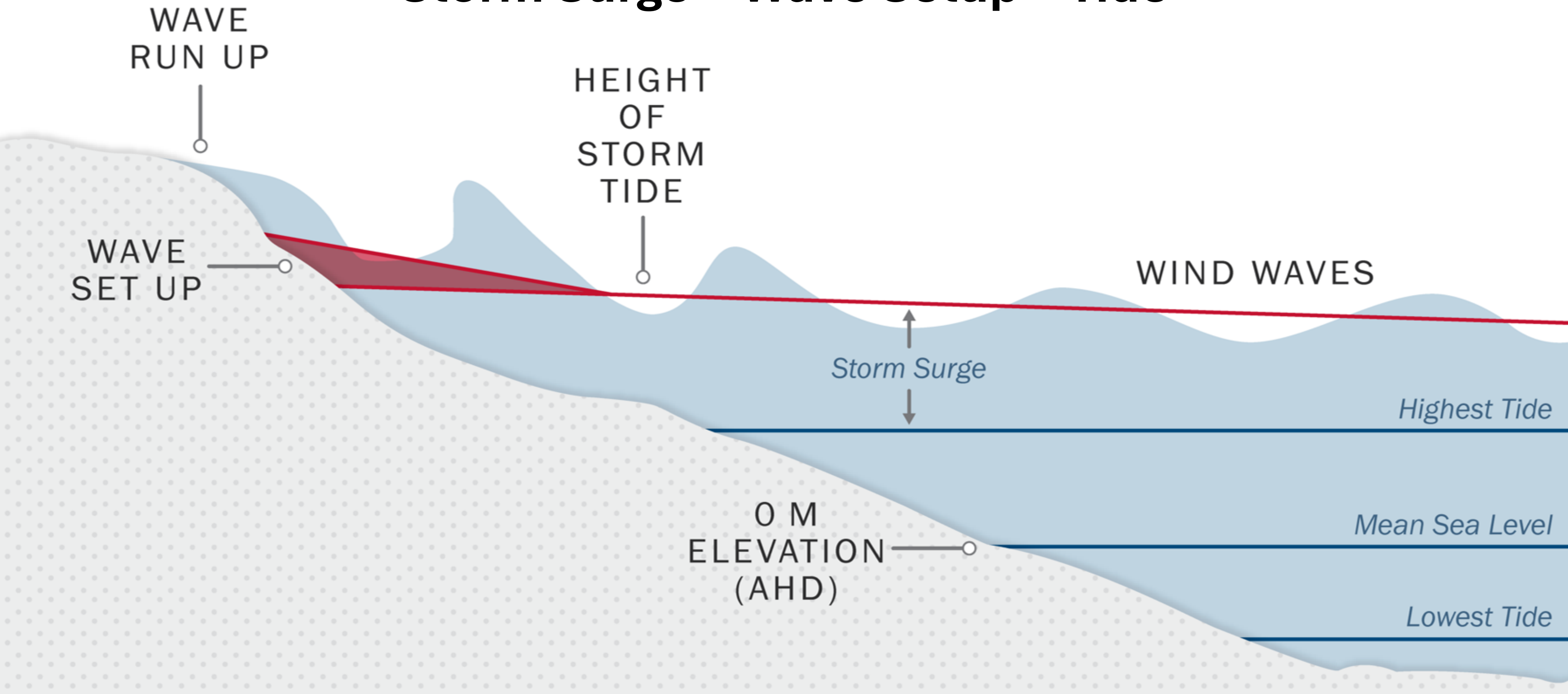
Wave and Wind Effects



Lee et al. (2013)
Published on Dynamics of Atmospheres and Oceans

Physical Mechanism (2)

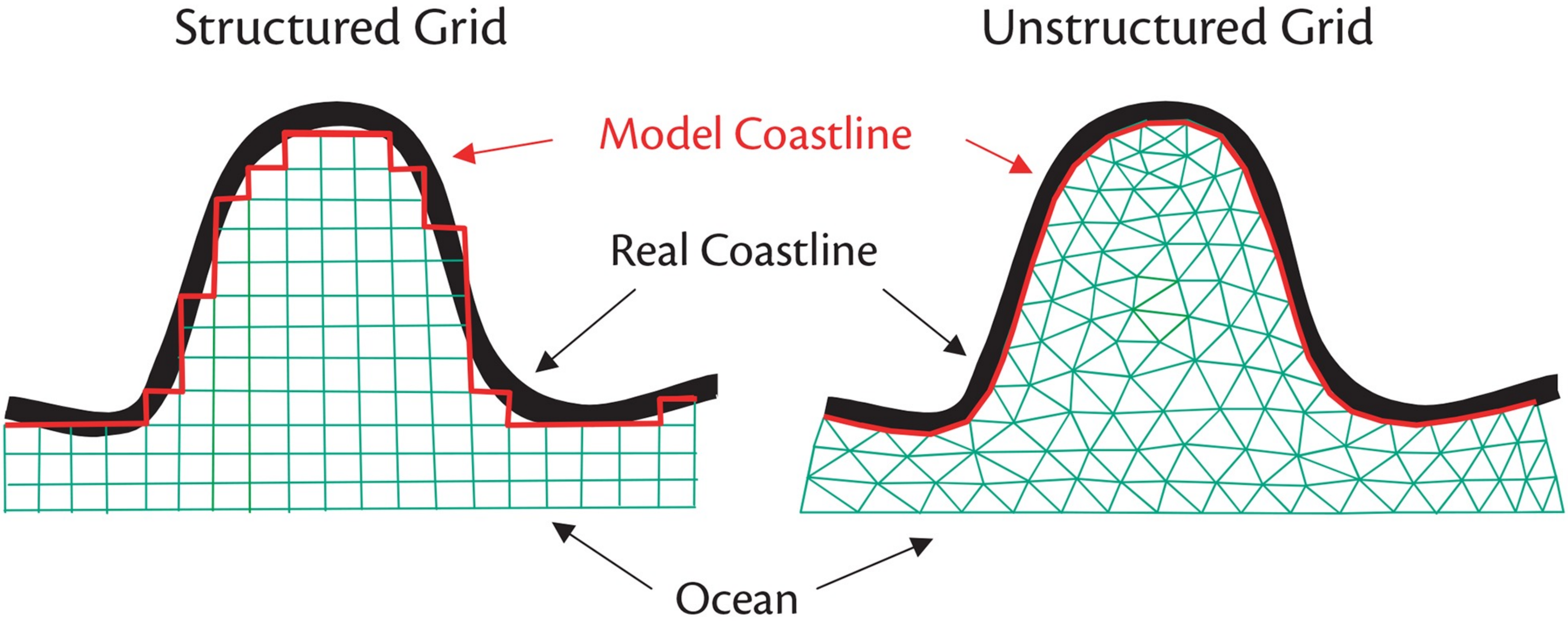
Storm Surge + Wave Setup + Tide



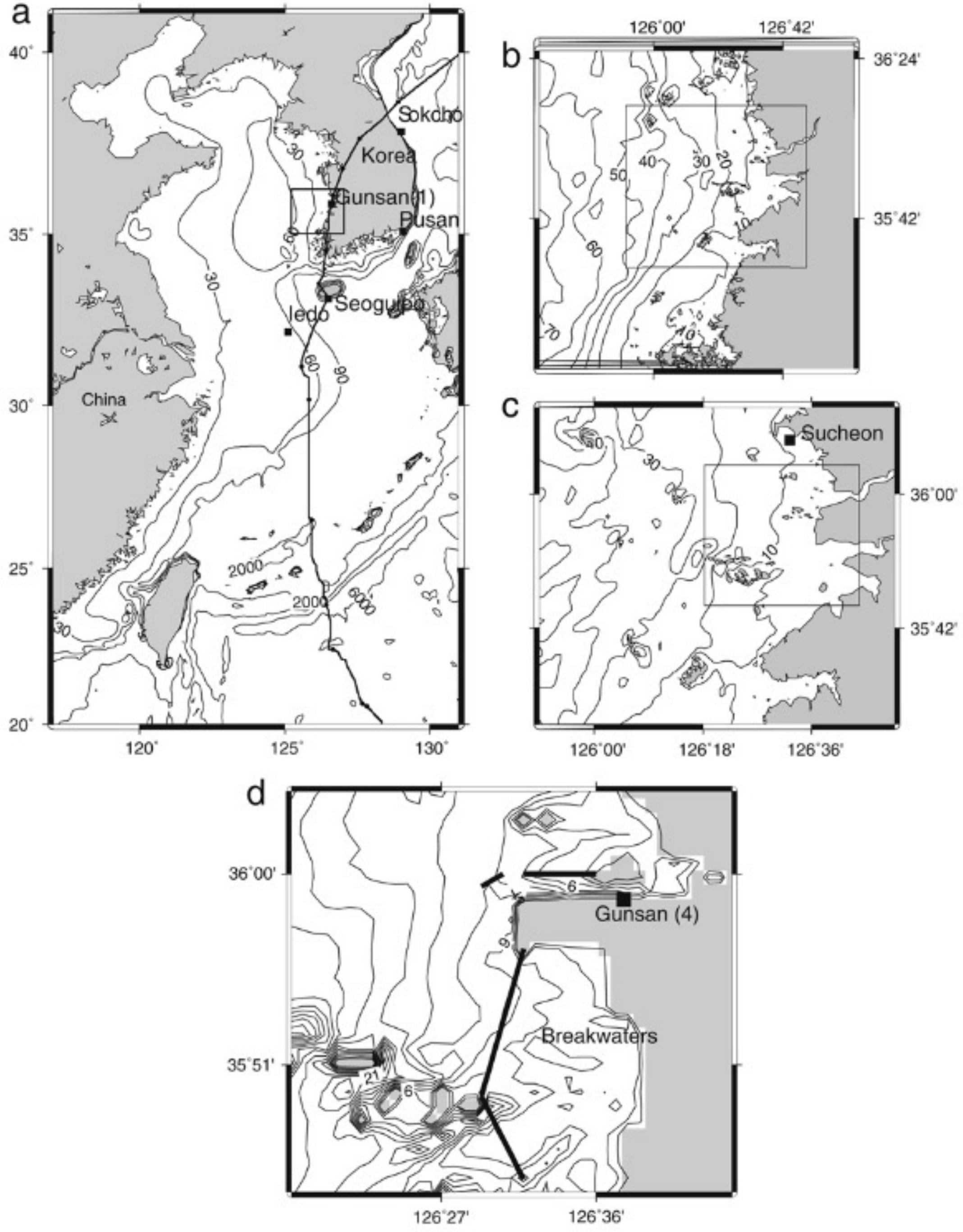
Source: https://www.nhc.noaa.gov/surge/images/totalWaterLevel.png

How do we simulate storm surge?

Shoreline in Hydrodynamic Modeling



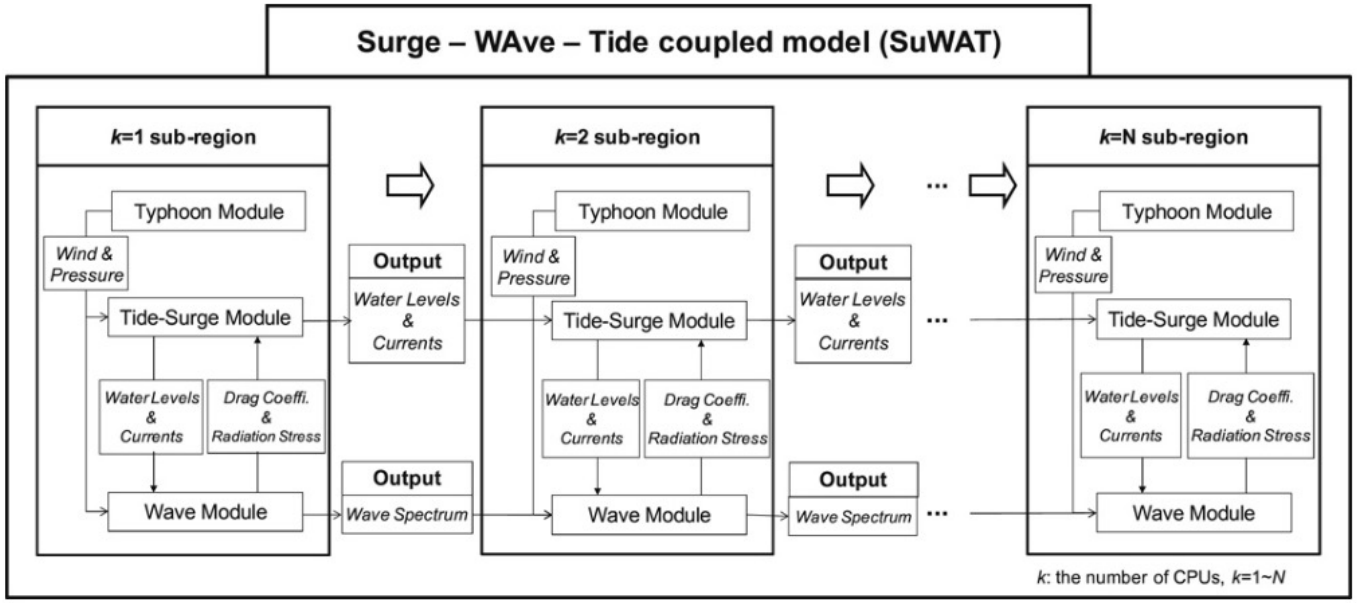
Source: https://www.unoceanprediction.org/en/resources/wiki/chapters/350



Grid Nesting in Storm Surge Modeling

- Computational efficiency compared to unstructured grids
- Grid generation is simpler than unstructured grids.

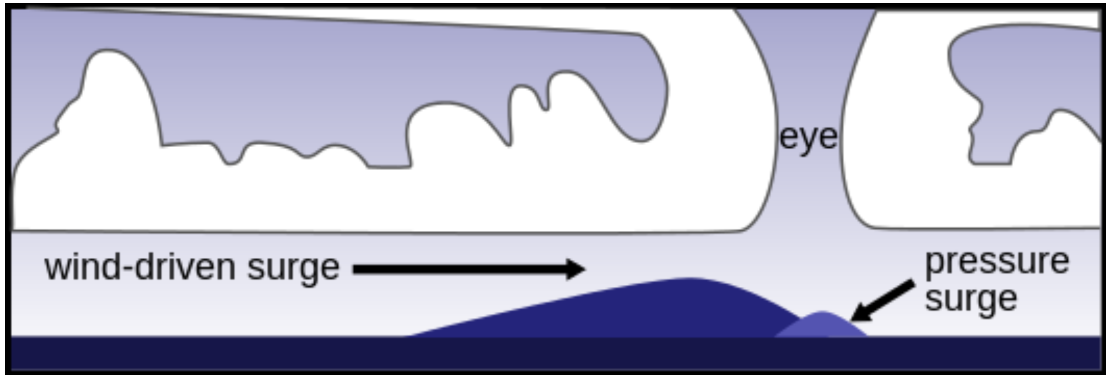
- But only a few regions can be covered by optimal grid sizes.



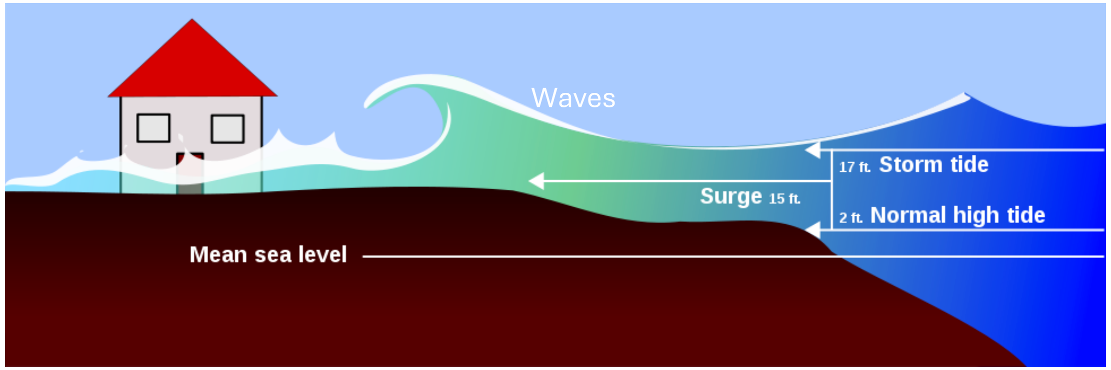
Kim et al. (2008; Applied Ocean Research)

Developed Surge-Tide-Wave Modeling Package

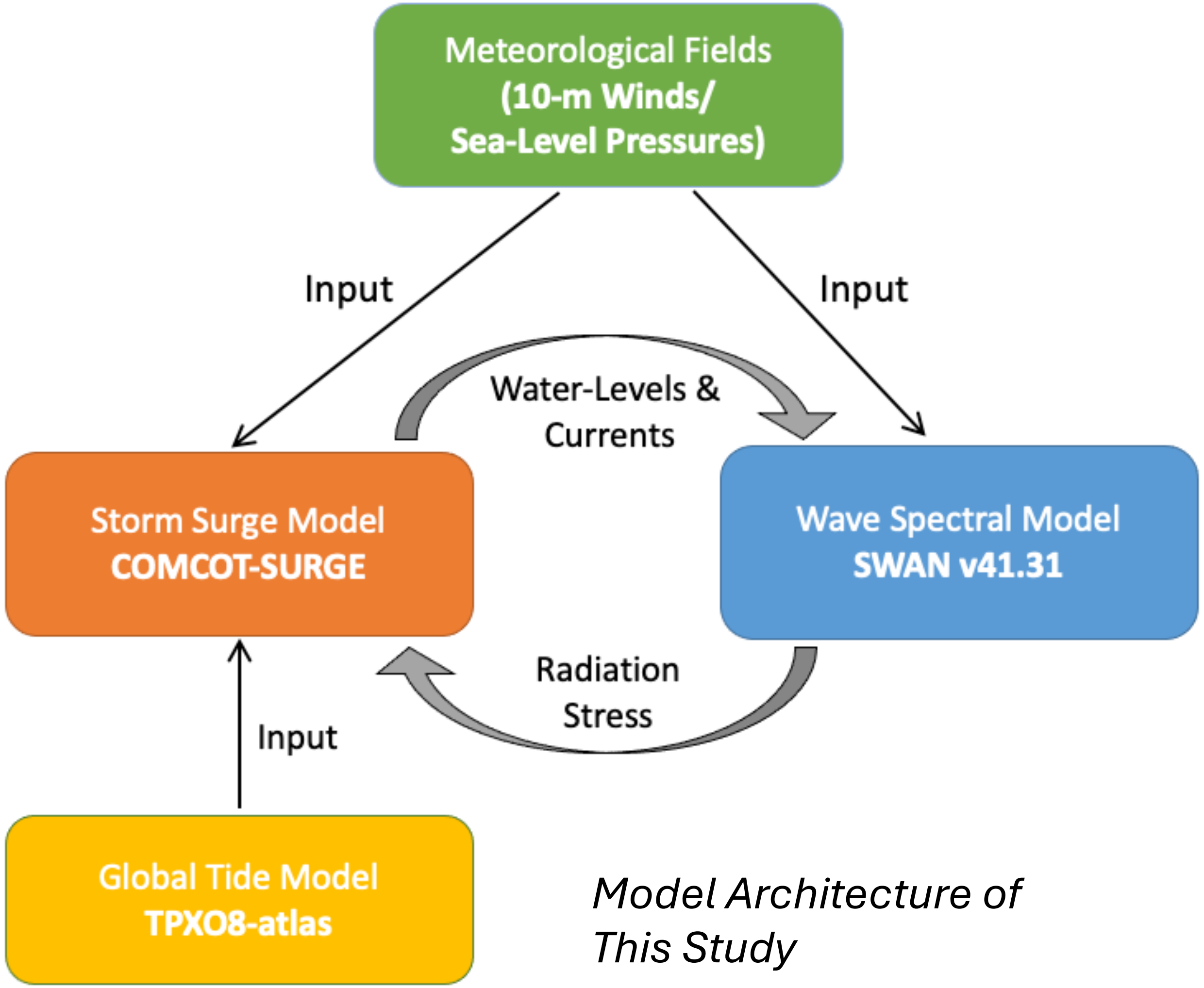
Storm Surges: (1) Sea-Level Pressure Gradient, (2) Wind shear Stress, (3) Wave-Enhanced Radiation Stress, (4) Tide Effect, (5) Coriolis Effect, and (6) Bathymetry Effect.



Sea Surface induced by typhoons (NHC, NOAA)



Tides and Waves with Storm Surges in Nearshore Regions (NHC, NOAA)



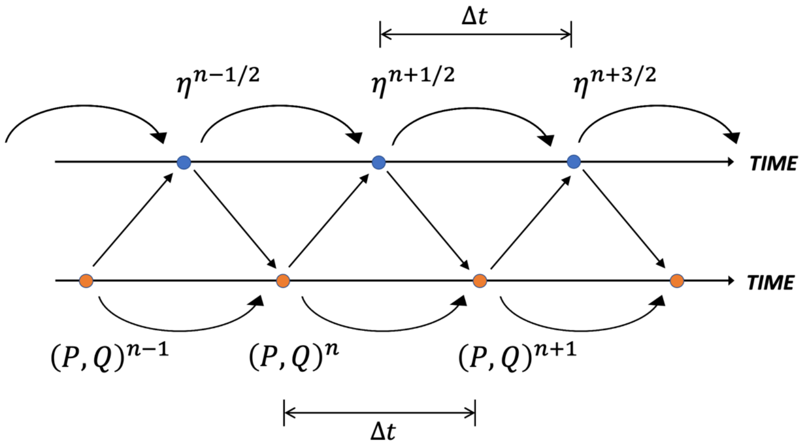
Model Architecture of This Study

Storm Surge Model – COMCOT-SURGE

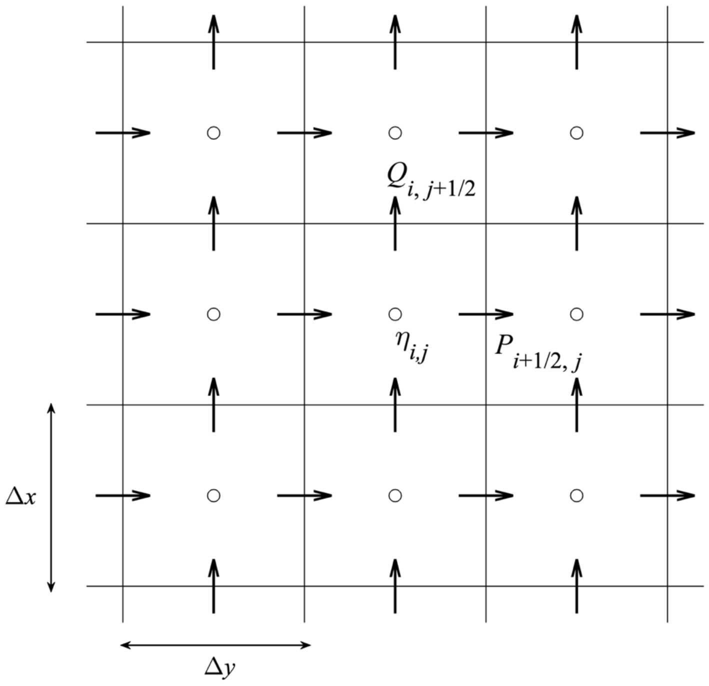
(COrnell Multi-Grid Coupled Tsunami Model – Storm Surge)

1. Moving boundary scheme for tracing a moving shoreline (Liu et al., 1995).
2. Upwind scheme solver for the advection terms (Liu et al., 1995).
3. OpenMp parallel computing function in COMCOT-SURGE (Lin et al., 2015).

Leap-Frog Scheme



Arakawa C Grid



Mass Equation

$$\frac{\partial \eta}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0$$

Momentum Equation

$$\frac{\partial P}{\partial t} + \frac{\partial}{\partial x}\left(\frac{P^2}{H}\right) + \frac{\partial}{\partial y}\left(\frac{PQ}{H}\right) - fQ = -gH\frac{\partial \eta}{\partial x} - \frac{H}{\rho_w}\frac{\partial P_a}{\partial x} + \frac{\rho_a C_d U_{10} U_{10}^x}{\rho_w} - \frac{gn^2}{H^{7/3}}P(P^2 + Q^2)^{1/2} + \frac{F_x}{\rho_w} + A_h\left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}\right)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{PQ}{H}\right) + \frac{\partial}{\partial y}\left(\frac{Q^2}{H}\right) + fP = -gH\frac{\partial \eta}{\partial y} - \frac{H}{\rho_w}\frac{\partial P_a}{\partial y} + \frac{\rho_a C_d U_{10} U_{10}^y}{\rho_w} - \frac{gn^2}{H^{7/3}}Q(P^2 + Q^2)^{1/2} + \frac{F_y}{\rho_w} + A_h\left(\frac{\partial^2 Q}{\partial x^2} + \frac{\partial^2 Q}{\partial y^2}\right)$$

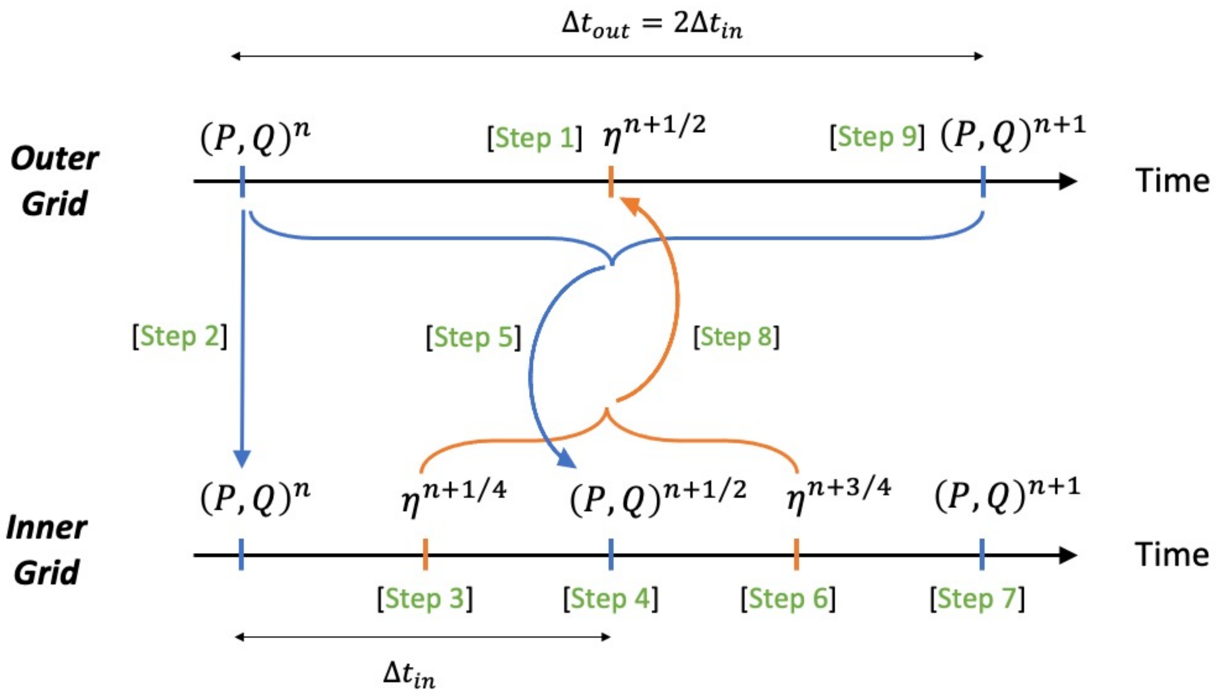
Time Variant | Advection Terms | Coriolis Force | Surface Gradient | Sea-Level Pressures | Wind Shear Stress | Bottom Friction | Radiation Stress | Horizontal Eddy Diffusion

Multi-Grid Nesting in COMCOT-SURGE

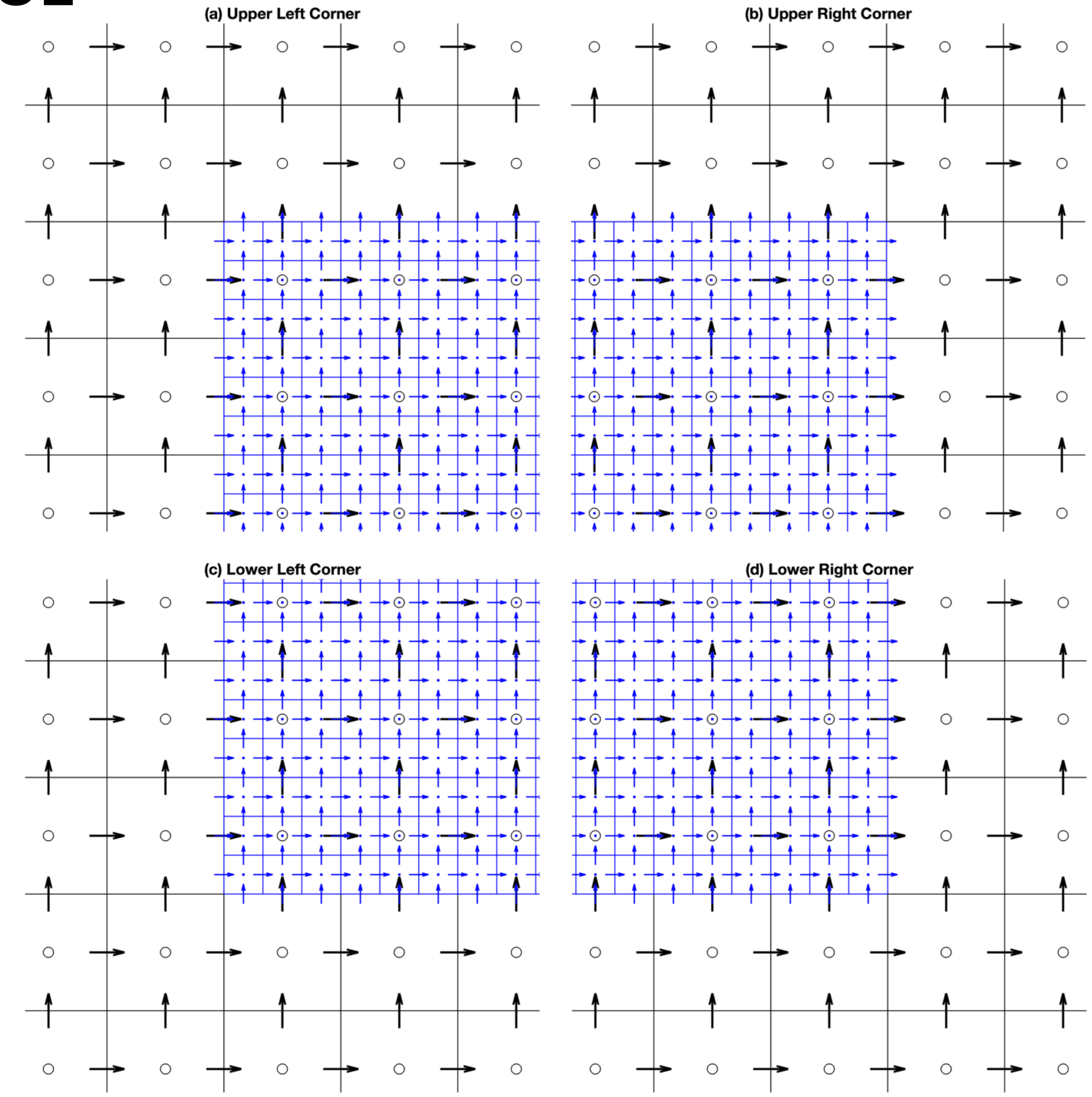
CFL (Courant–Friedrichs–Lewy) Condition

$$\Delta t \leq C_r \frac{\Delta s}{\sqrt{2gh_{max}}}$$

Grid Nesting in Time Domain



Grid Nesting in Space Domain



Spectral Wave Model – SWAN (Simulating WAves Nearshore)

G.E. on Cartesian Coordinate System

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}$$

Source and Sink Terms in SWAN Model

Wave growth by the Wind (Linear: Cavaleri and Malanotte-Rizzoli, 1981; Exponential: Komen et al.,1984)

Triad (Lumped Triad Approximation; Eldeberky, 1996) and Quadruplet wave-wave interaction (Discrete Interaction Approximation; Hasselmann et al., 1985)

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br}$$

Wave decay due to white capping (Komen et al., 1984), bottom friction (JONSWAP; Hasselmann et al., 1973) and depth-induced wave breaking (Battjes and Jansen, 1978)

Total energy density

$$E(f) = \int_0^{2\pi} E(f,\theta)d\theta$$

Action density

$$N = E/\sigma$$

Radiation Stress

The depth-integrated radiation stresses are first introduced by Longuet-Higgins and Stewart (1960, 1962, 1963, 1964) and integrated for random short-crested waves over spectrum by Battjes (1972).

$$S_{xx} = \rho_w g \iint \left(\frac{C_g}{C} cos^2\theta + \frac{C_g}{C} - \frac{1}{2}\right) N\sigma d\sigma\, d\theta$$

$$S_{yy} = \rho_w g \iint \left(\frac{C_g}{C} sin^2\theta + \frac{C_g}{C} - \frac{1}{2}\right) N\sigma d\sigma\, d\theta$$

$$S_{xy} = \rho_w g \iint (cos\theta sin\theta) N\sigma d\sigma\, d\theta$$

$$S_{yx} = S_{xy}$$

Model Validation

Solitary Wave Runup on a Conical Island

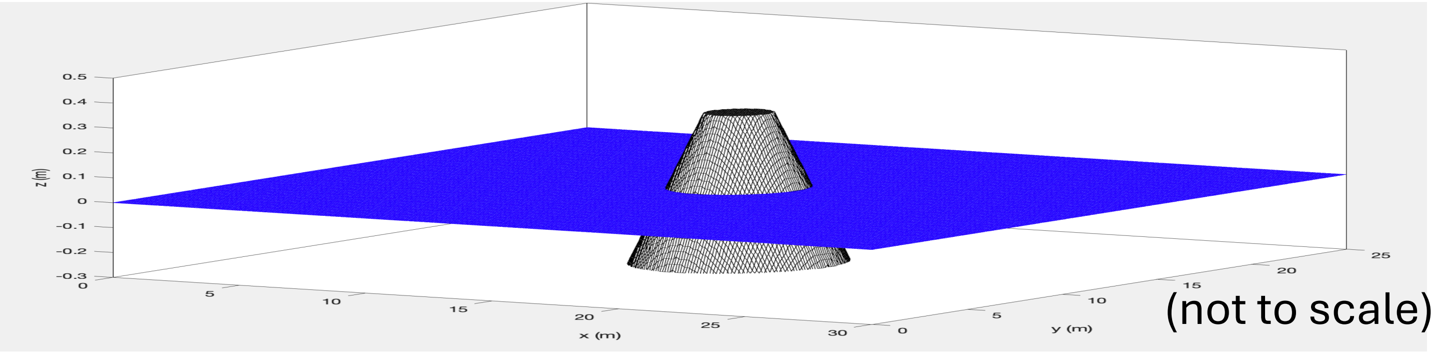
(Liu et al., 1995; Briggs et al., 1995; Yeh et al., 1994)

Incident Wave Condition

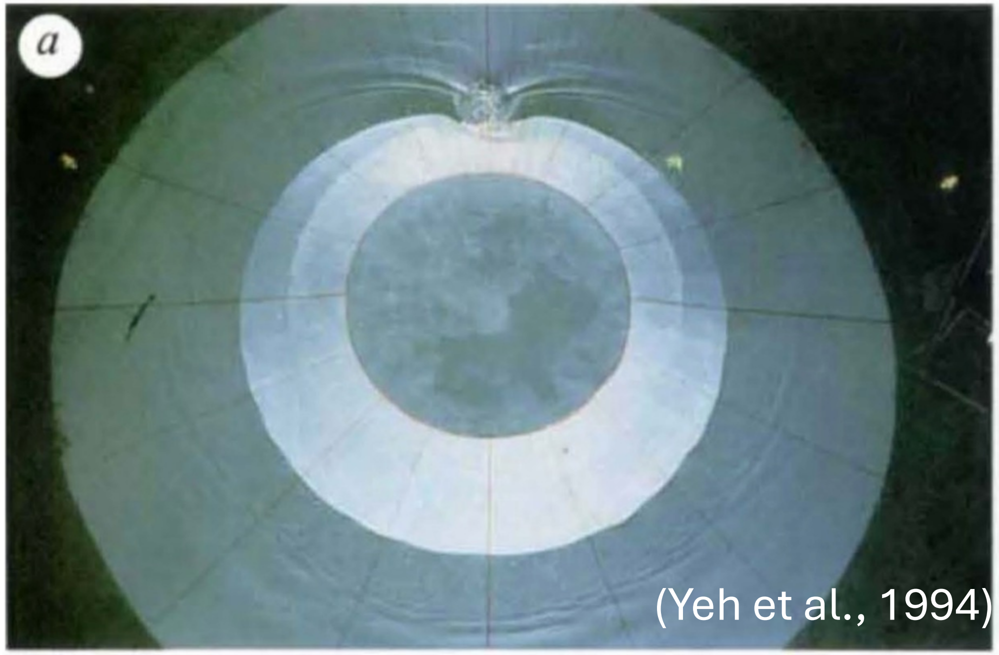
Case	Wave Nonlinearity (A/d)	Solitary Wave Height A (unit: m)	Still Water Depth d (unit: m)
Case A	0.045	0.0144	0.32
Case B	0.091	0.0291	0.32
Case C	0.181	0.0579	0.32

3D Presentation of Topography by MATLAB

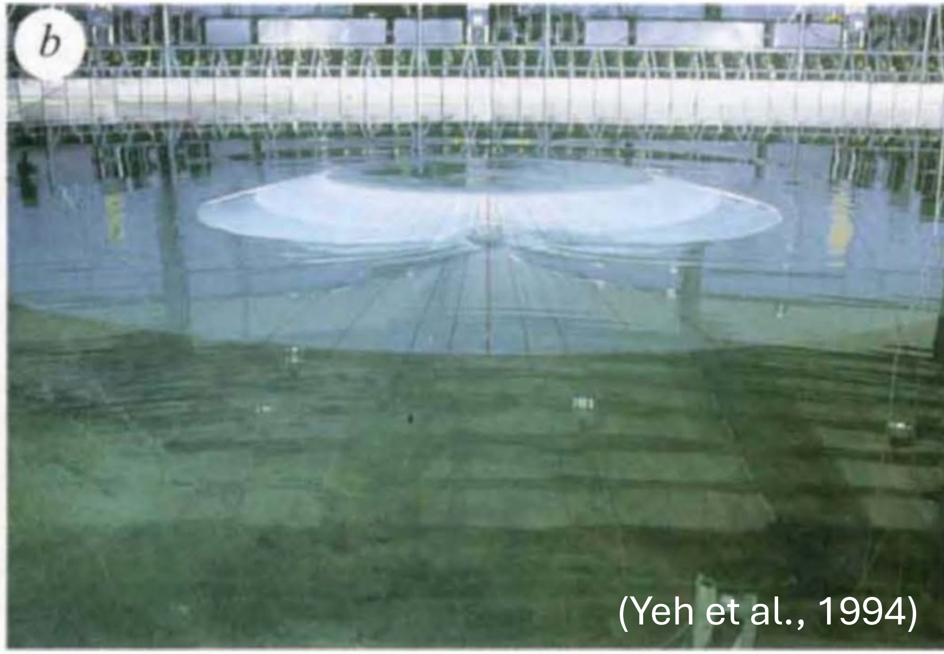
(z = 0.0 indicates the still water surface)



(not to scale)

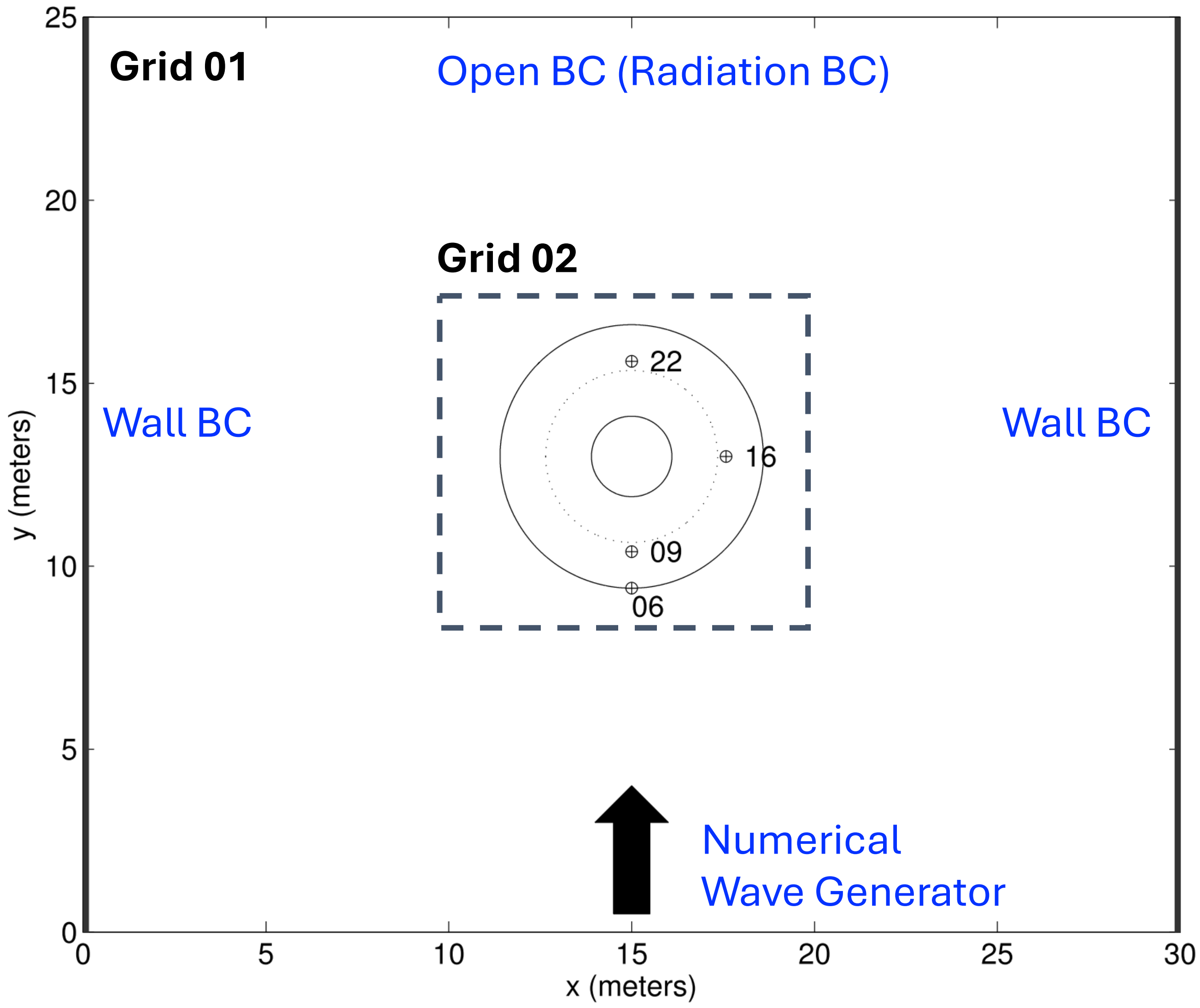


(Yeh et al., 1994)



(Yeh et al., 1994)

Computational Settings



Wang and Power (2011)

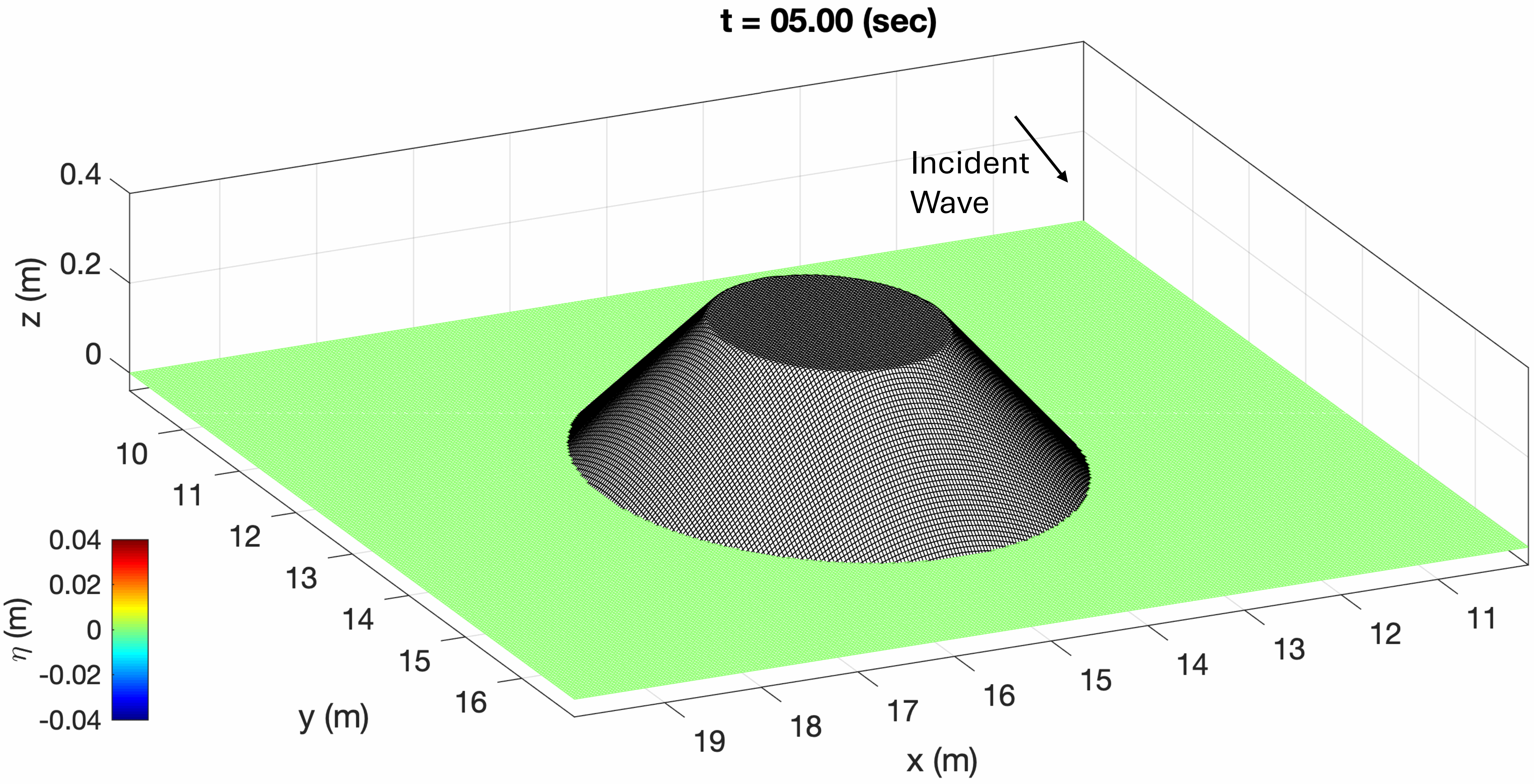
Grid 01
dx = dy = 0.1 [m]; dt = 0.01 [sec]
Linear SWEs (Frictionless)

Grid 02
dx = dy = 0.033 [m]; dt = 0.05 [sec]
Nonlinear SWEs (Frictional, n = 0.013)

Wave Gauge Locations

Gauge Number	X Location (Unit: m)	Y Location (Unit: m)
G6	15.00	9.40
G9	15.00	10.40
G16	17.58	13.00
G22	15.00	15.60

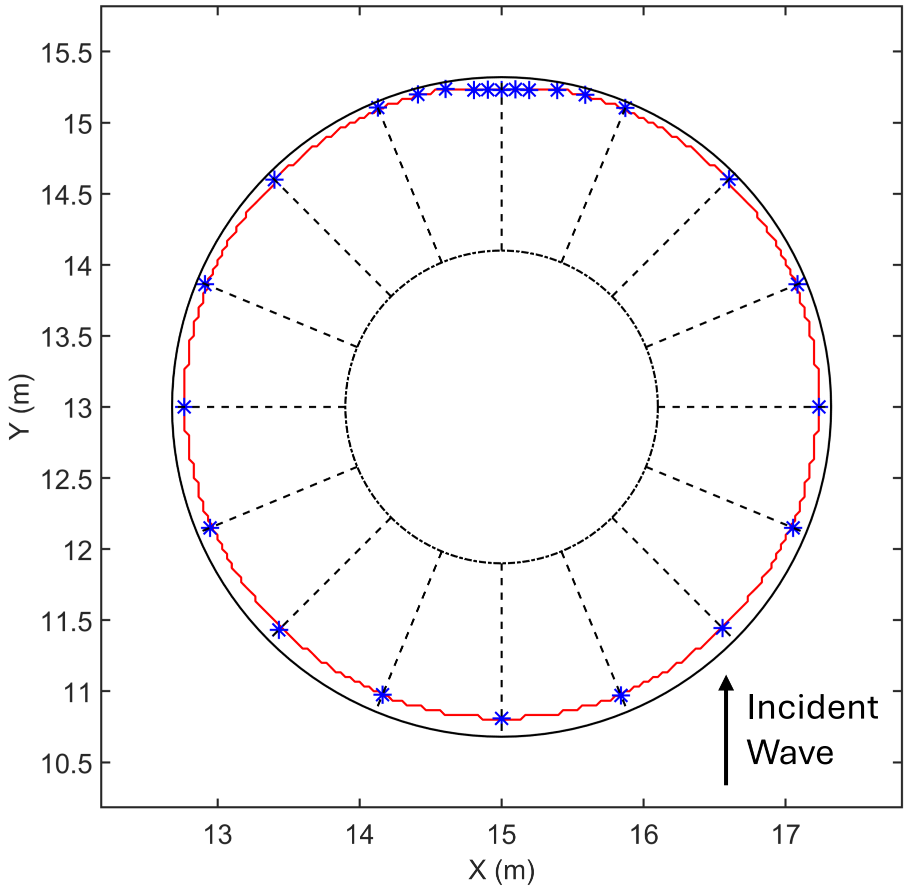
Case B - *H/d* = 0.091



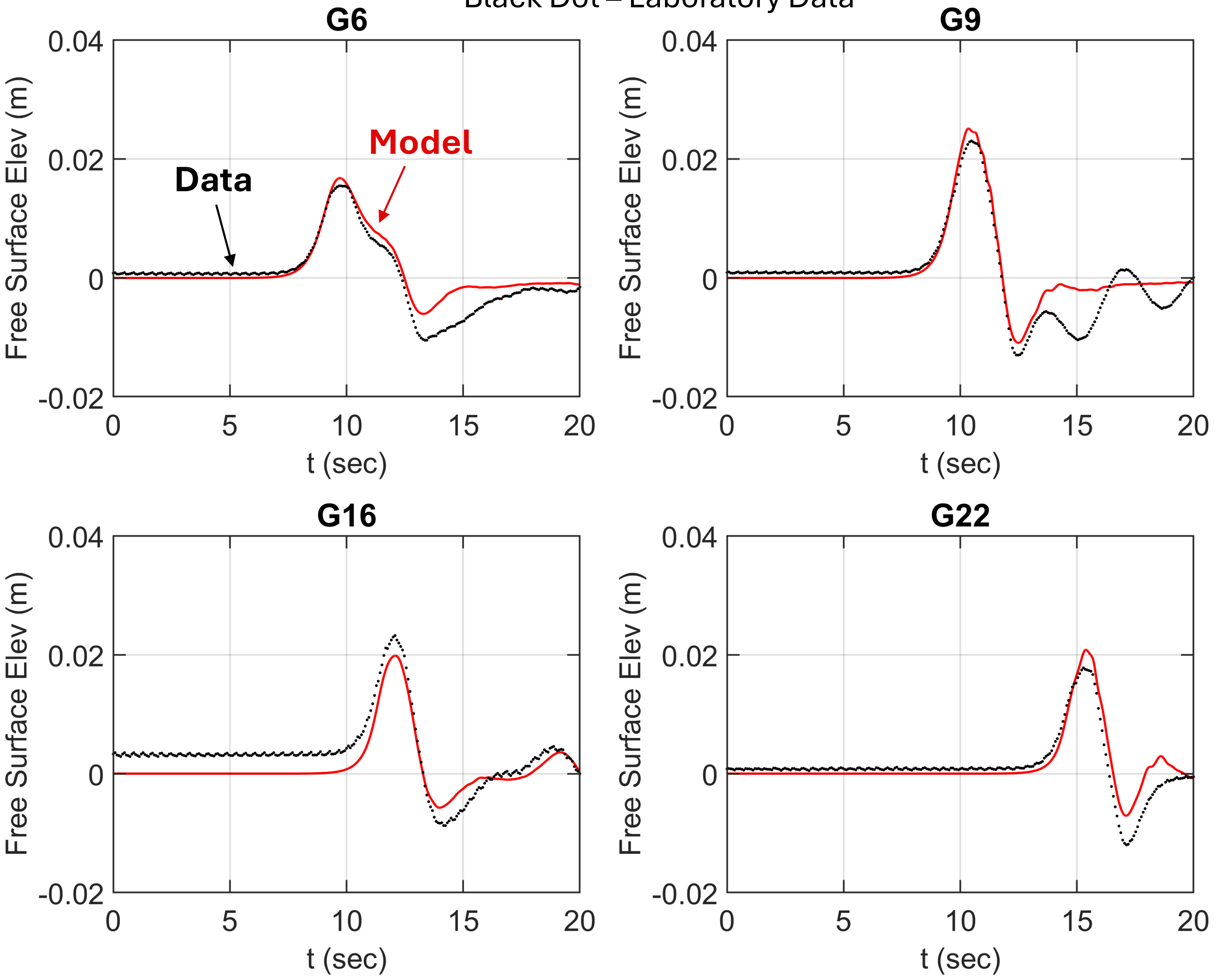
Model Comparison with Lab Experiment Data

(Case A - *A/d* = 0.045)

Red Line – Numerical Solution
Blue Asterisk – Experimental Data

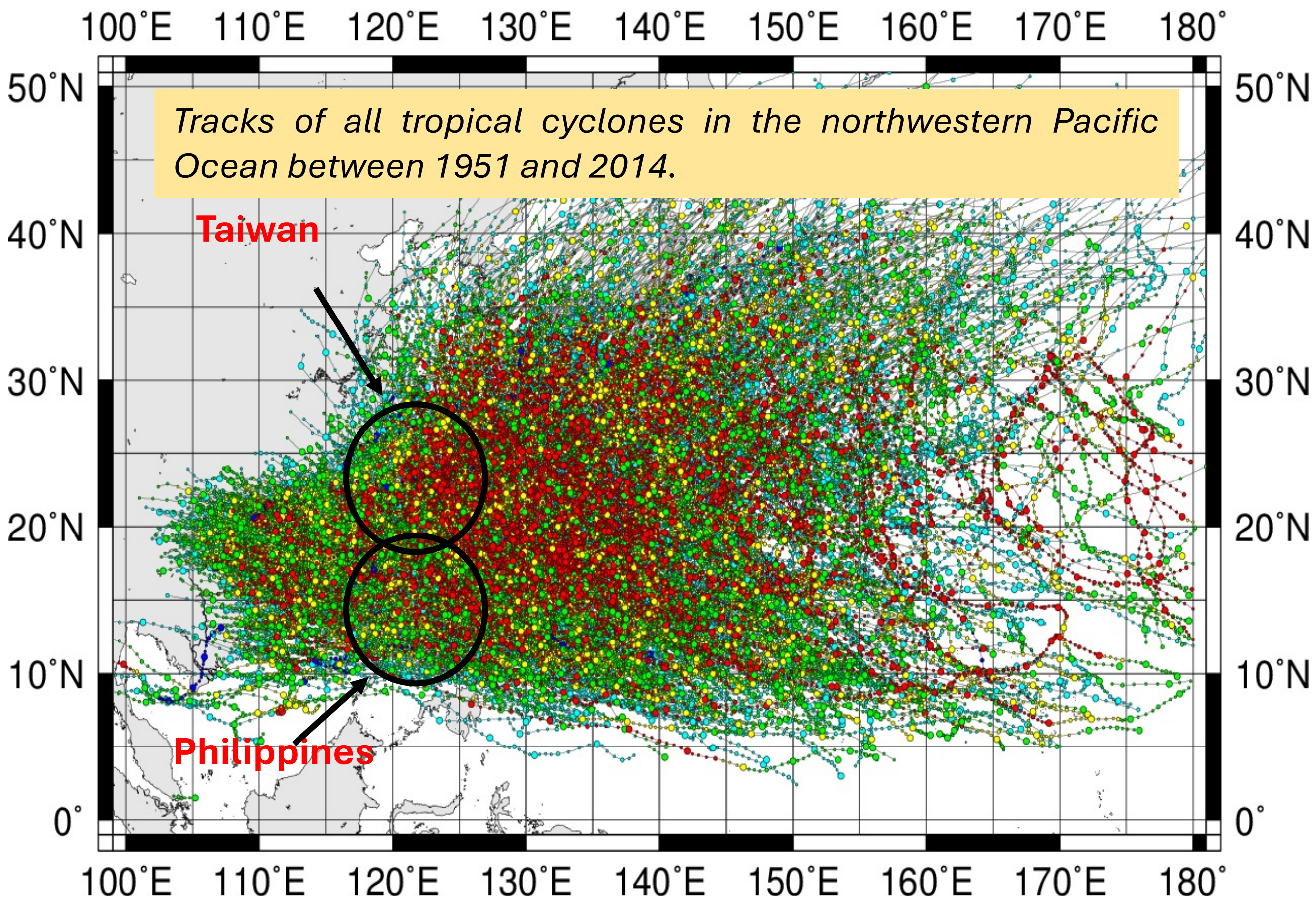


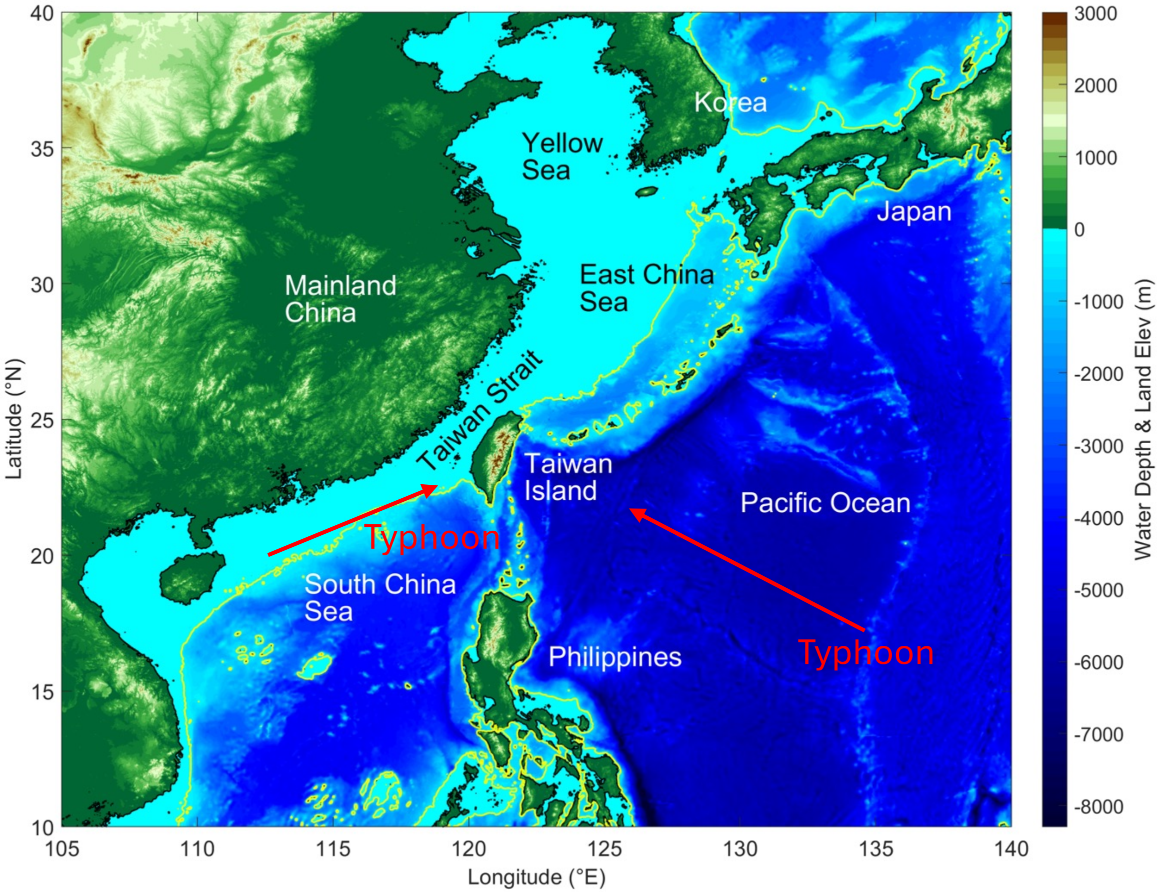
Red Line – Numerical Solution
Black Dot – Laboratory Data



Typhoon-Prone Regions in East Asia

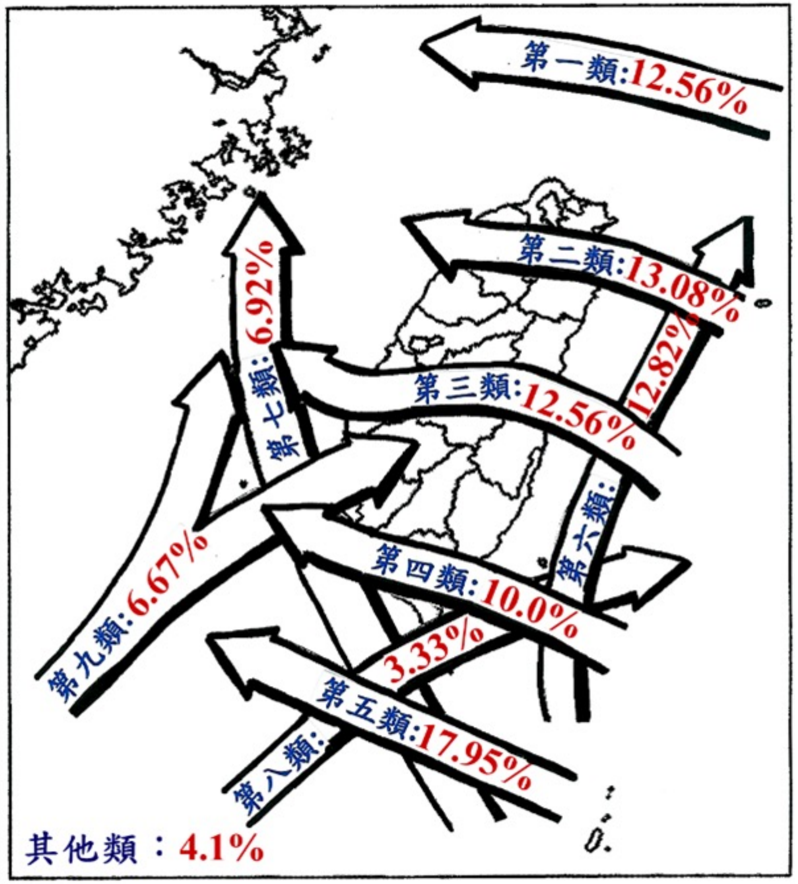
In the future, the numbers of typhoons tend to decrease <u>but increase in intensity</u> (see Emanuel, 2005; Schiermeier, 2013; Lin and Chan, 2015; Sun et al., 2017), making coastal regions more susceptible to storm surges.





Taiwan was attacked by 3 to 4 typhoons per year on average in the past years (Wu and Kuo, 1999; Liang et al., 2017).

Typhoons in Taiwan



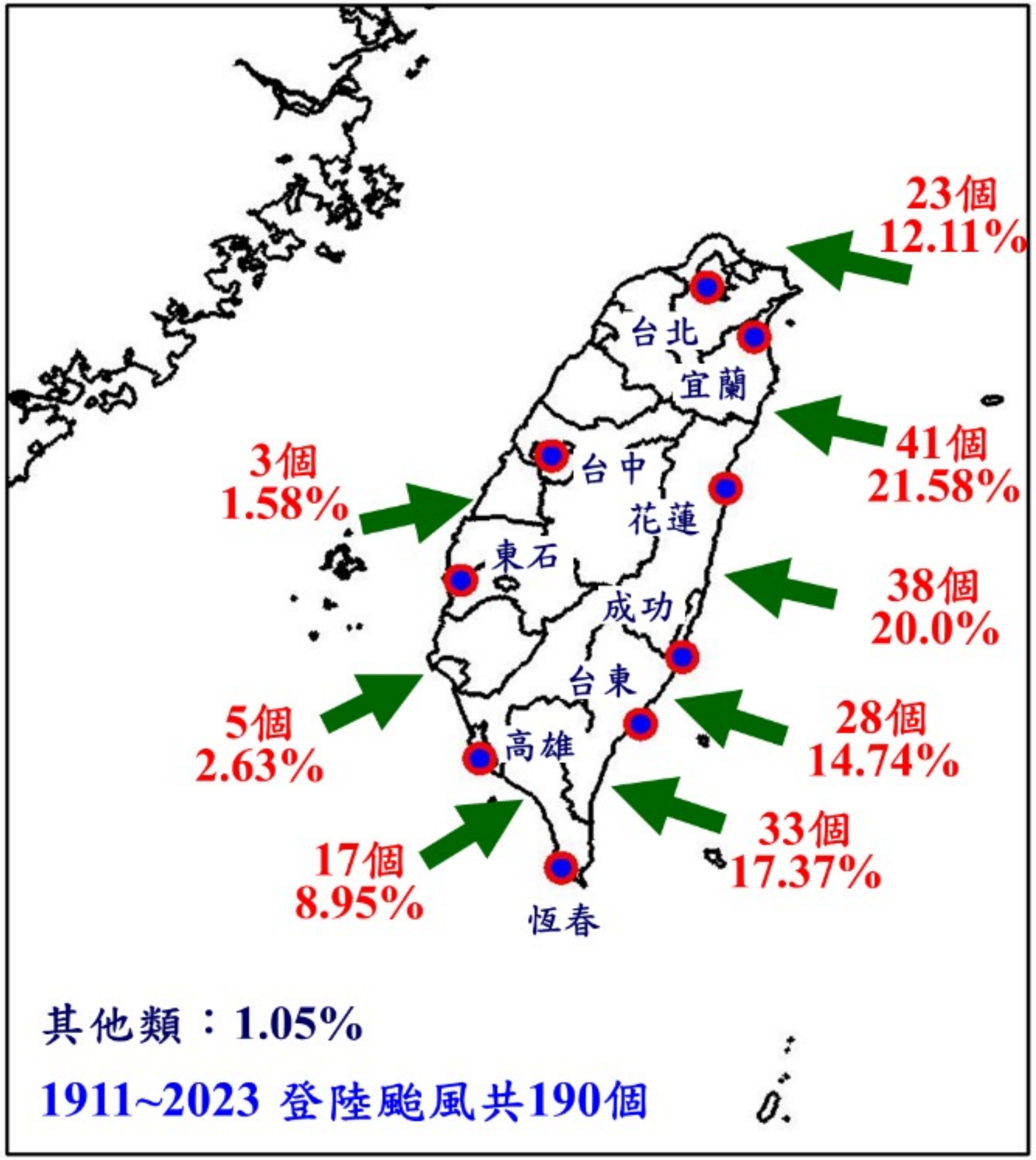
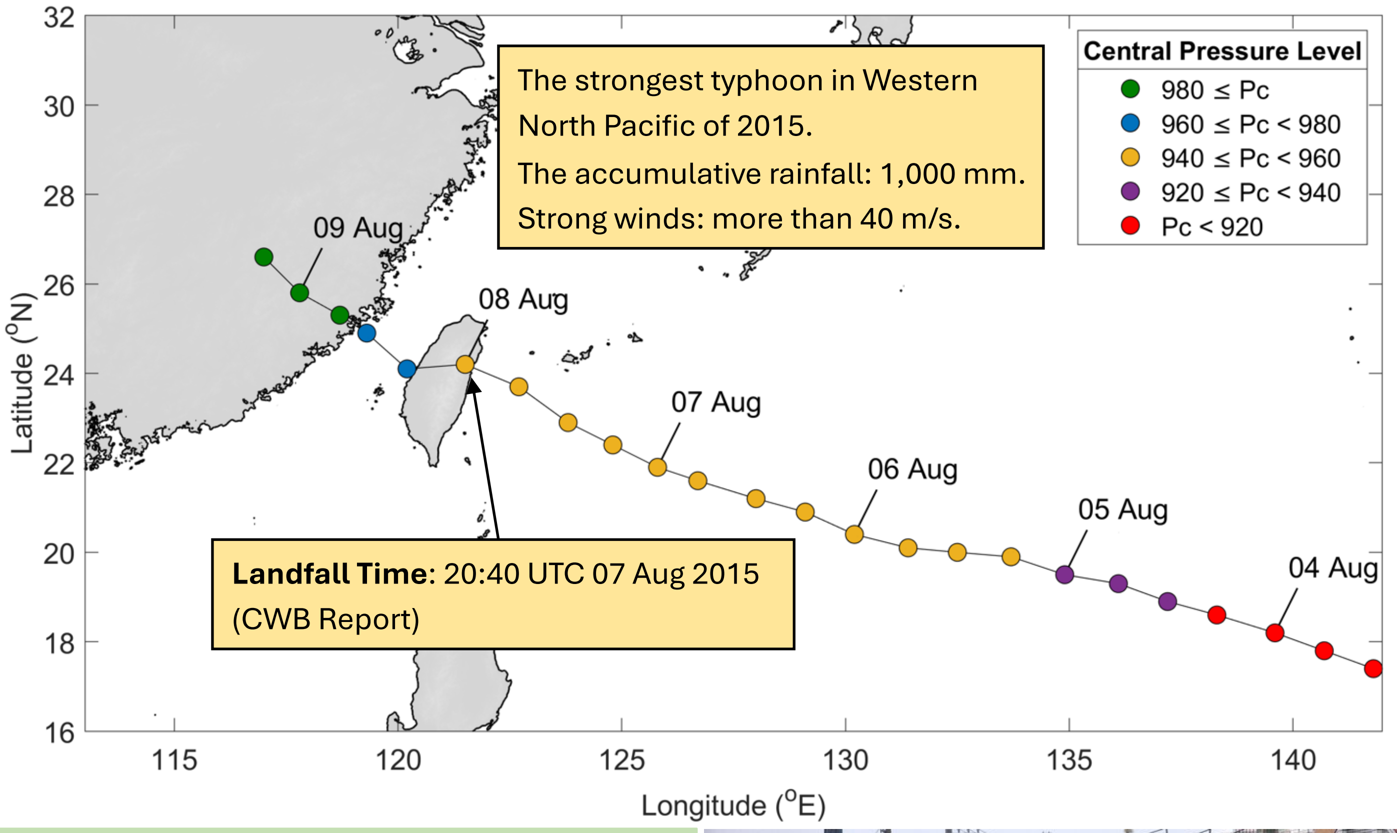


表7　西元1911年至2023年颱風侵襲臺灣各月個數

月份	4月	5月	6月	7月	8月	9月	10月	11月	12月
個數	1	9	25	97	108	91	31	12	1
平均	0.01	0.08	0.23	0.87	0.97	0.82	0.28	0.11	0.01

CWA: https://www.cwa.gov.tw/V8/C/K/Encyclopedia/typhoon/typhoon_list02.html#typhoon-38

2015 Super Typhoon Soudelor



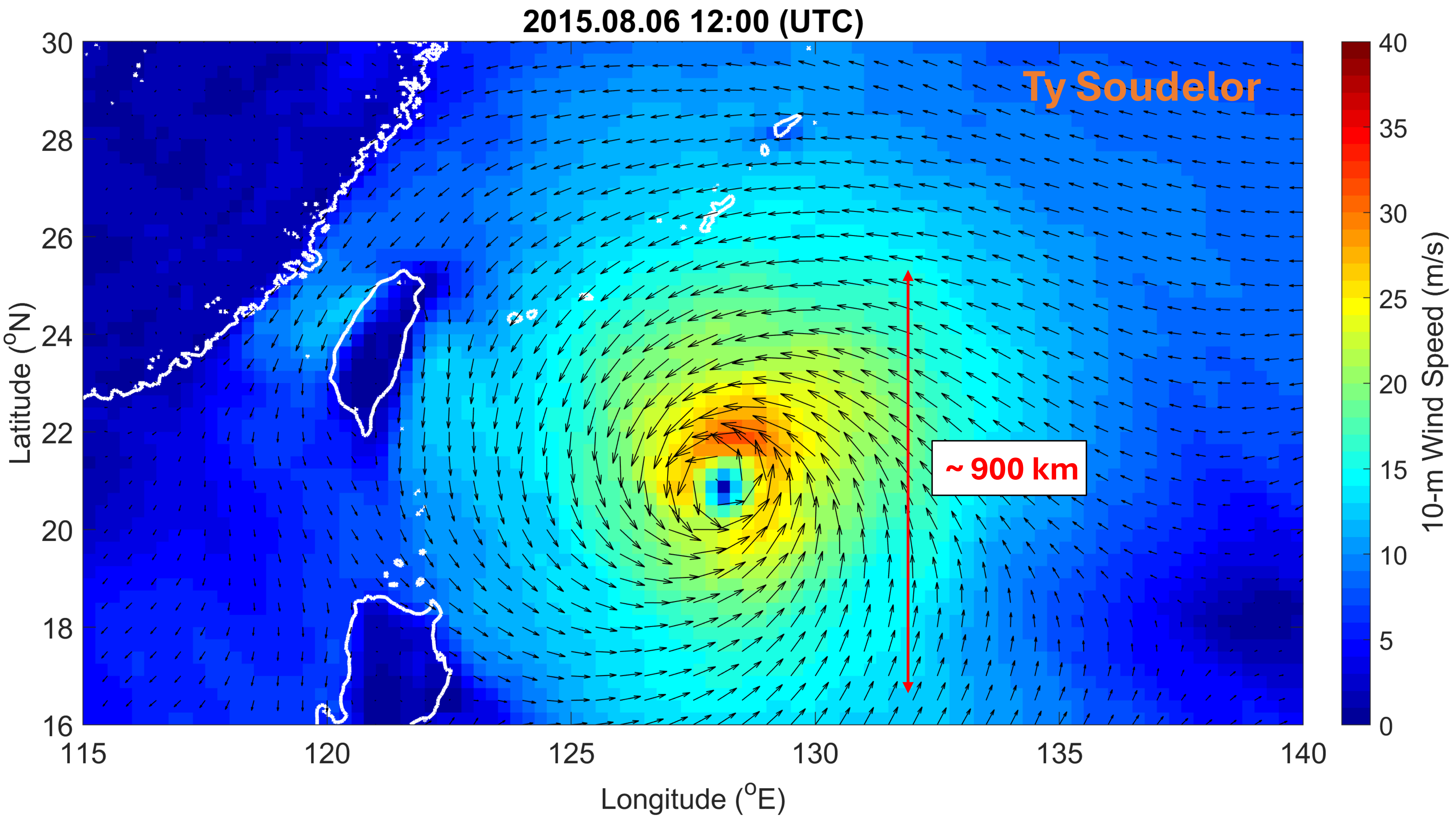
Waves in nearshore regions of eastern Taiwan.
(自由時報記者王秀亭攝)

The flood in low-lying region at Ilan because of Typhoon Soudelor. (中央社記者沈如峰宜蘭縣)

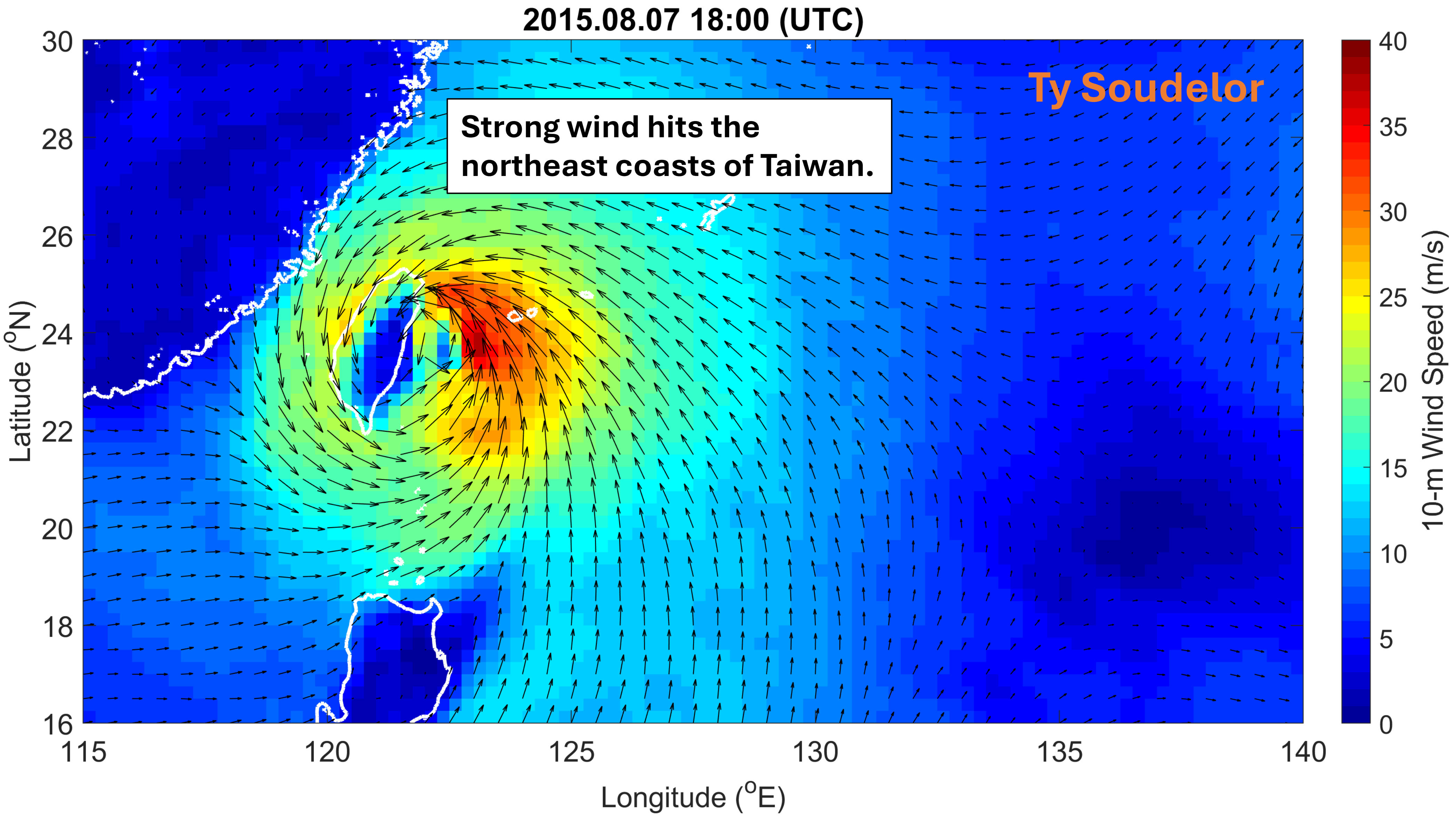
Best-track data from JTWC (Joint Typhoon Warning Center)

YY	MM	DD	HR	Lat	Lon	Vmax (m/s)	MSLP (hPa)
2015	8	3	0	16.2	144.0	56.59	941
2015	8	3	6	16.9	142.9	64.31	929
2015	8	3	12	17.4	141.8	72.02	918
2015	8	3	18	17.8	140.7	79.74	907
2015	8	4	0	18.2	139.6	77.17	911
2015	8	4	6	18.6	138.3	72.02	918
2015	8	4	12	18.9	137.2	69.45	922
2015	8	4	18	19.3	136.1	64.31	929
2015	8	5	0	19.5	134.9	59.16	937
2015	8	5	6	19.9	133.7	54.02	944
2015	8	5	12	20.0	132.5	51.44	948
2015	8	5	18	20.1	131.4	48.87	952
2015	8	6	0	20.4	130.2	46.30	956
2015	8	6	6	20.9	129.1	43.73	959
2015	8	6	12	21.2	128.0	46.30	956
2015	8	6	18	21.6	126.7	48.87	952
2015	8	7	0	21.9	125.8	51.44	948
2015	8	7	6	22.4	124.8	54.02	944
2015	8	7	12	22.9	123.8	54.02	944
2015	8	7	18	23.7	122.7	51.44	948
2015	8	8	0	24.2	121.5	48.87	952
2015	8	8	6	24.1	120.2	38.58	967
2015	8	8	12	24.9	119.3	36.01	970
2015	8	8	18	25.3	118.7	28.29	982
2015	8	9	0	25.8	117.8	20.58	993
2015	8	9	6	26.6	117.0	18.01	996

ECMWF ERA5 10-m Winds (1)



ECMWF ERA5 10-m Winds (2)



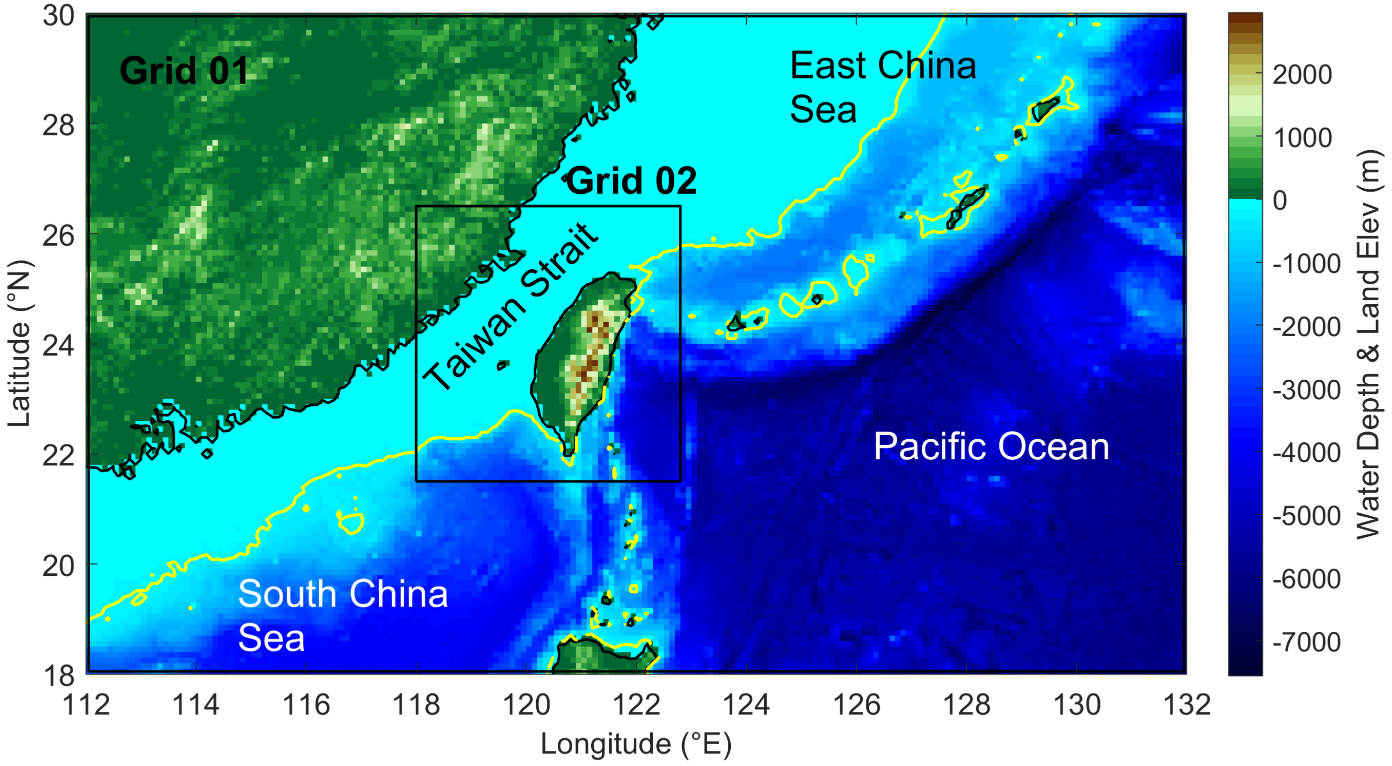
Hindcast Simulations for Storm Surges, Tides, and Waves

COMCOT-SURGE: Grid 01 (linear and frictionless); Grids 02-08 (nonlinear and frictional, n = 0.025).

SWAN: 36 bins (wave direction from 0 to 360 deg) and 36 bins (wave frequency from 0.03 *Hz* to 1.0 *Hz*)

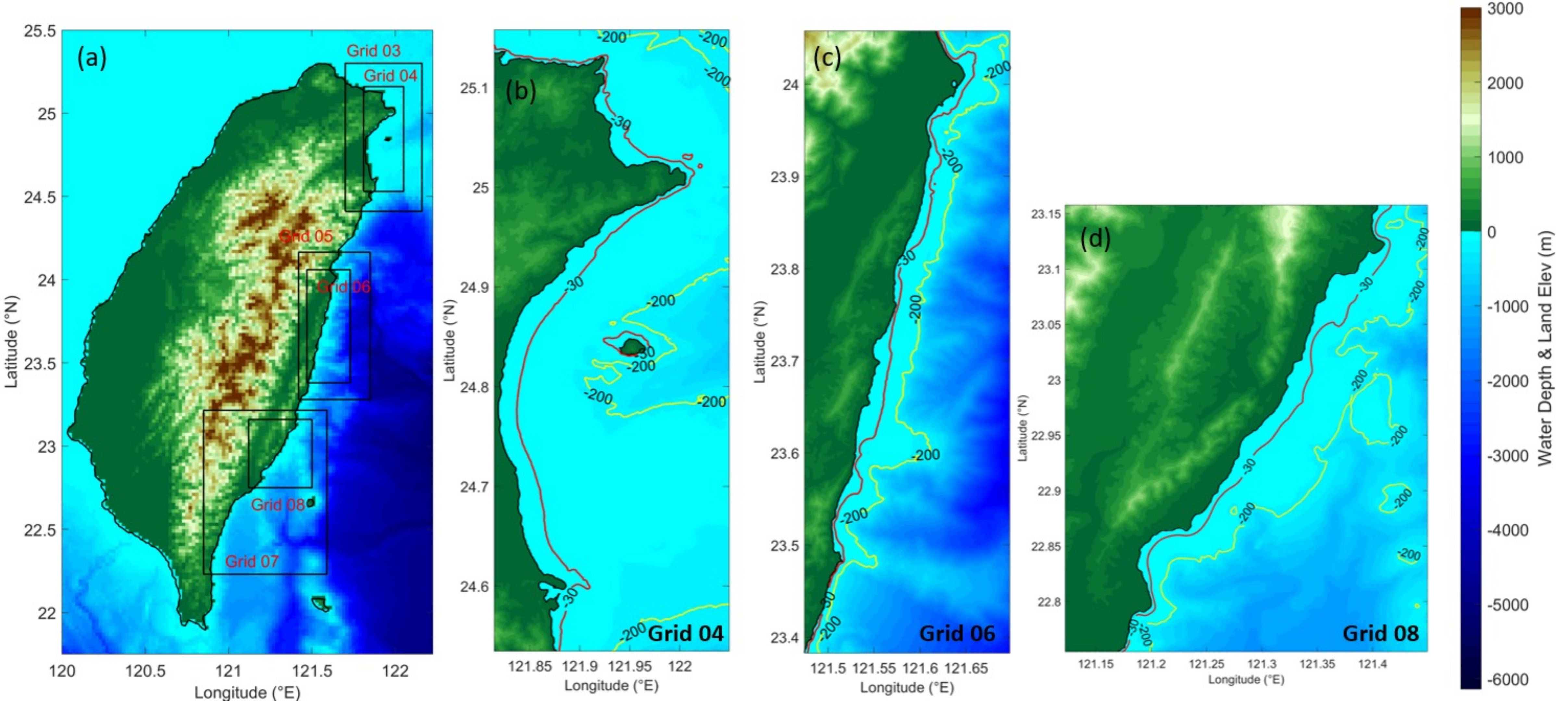
TPXO8-atlas: Tide elevations along the outermost boundaries of the first layer every 600 sec.

*The wind-drag coefficient proposed by Wu (1980, 1982) with an imposed lower bound limit of WAMDI (1988) is used.



Grid	Grid Level	Domain	Grid Size (Unit: deg)	Time Step (Unit: sec)		Bathymetry
				COMCOT-SURGE	SWAN	
01	1st	112.0 °E - 132.0 °E 18.0 °N – 30.0 °N	0.1 (~ 12 km)	1.0	600.0	ETOPO1
02	2nd	118.0 °E – 122.8 °E 21.5 °N – 26.5 °N	0.02 (~2.2 km)	0.5	600.0	MOST-TW 1000m
03	3rd	121.7 E – 122.16 °E 24.41 °N - 25.30 °N	0.004 (~ 0.4 km)	0.25	600.0	MOST-TW 1000m
04	4th	121.81 °E – 122.05 °E 24.53 °N– 25.16 °N	0.0008 (~92 m)	0.125	600.0	MOST-TW 200m
05	3rd	121.42 °E – 121.85 °E 23.28 °N – 24.165 °N	0.004 (~ 0.4 km)	0.25	600.0	MOST-TW 1000m
06	4th	121.47 °E - 121.7 °E 23.38 °N – 24.06 °N	0.0008 (~92 m)	0.125	600.0	MOST-TW 200m
07	3rd	120.85 °E – 121.59 °E 22.23 °N – 23.215 °N	0.004 (~ 0.4 km)	0.25	600.0	MOST-TW 1000m
08	4th	121.12 °E – 121.45 °E 22.75 °N – 23.16 °N	0.0008 (~92 m)	0.125	600.0	MOST-TW 200m

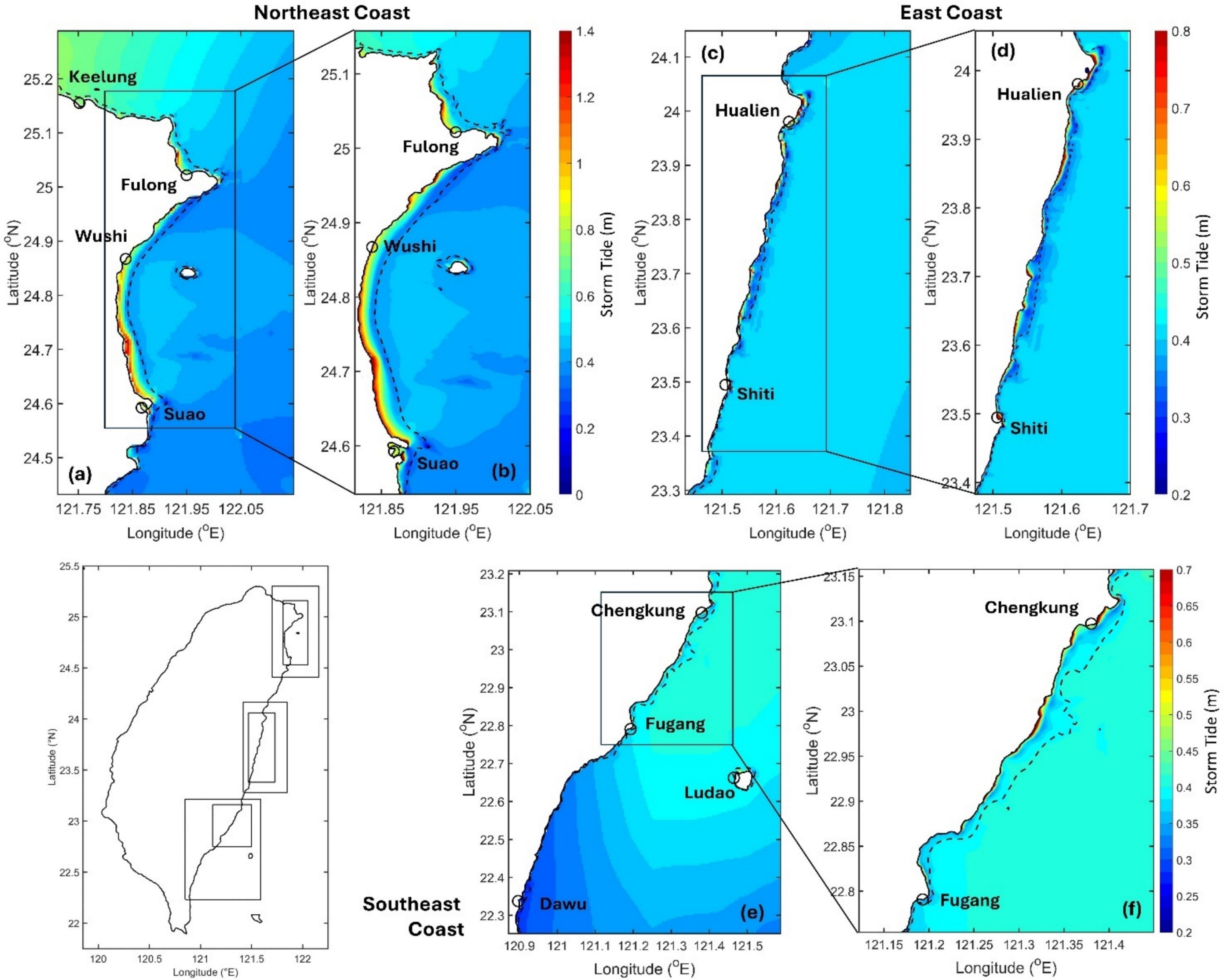
Finer Nested Grid Domains for Nearshore Regions (Continued)

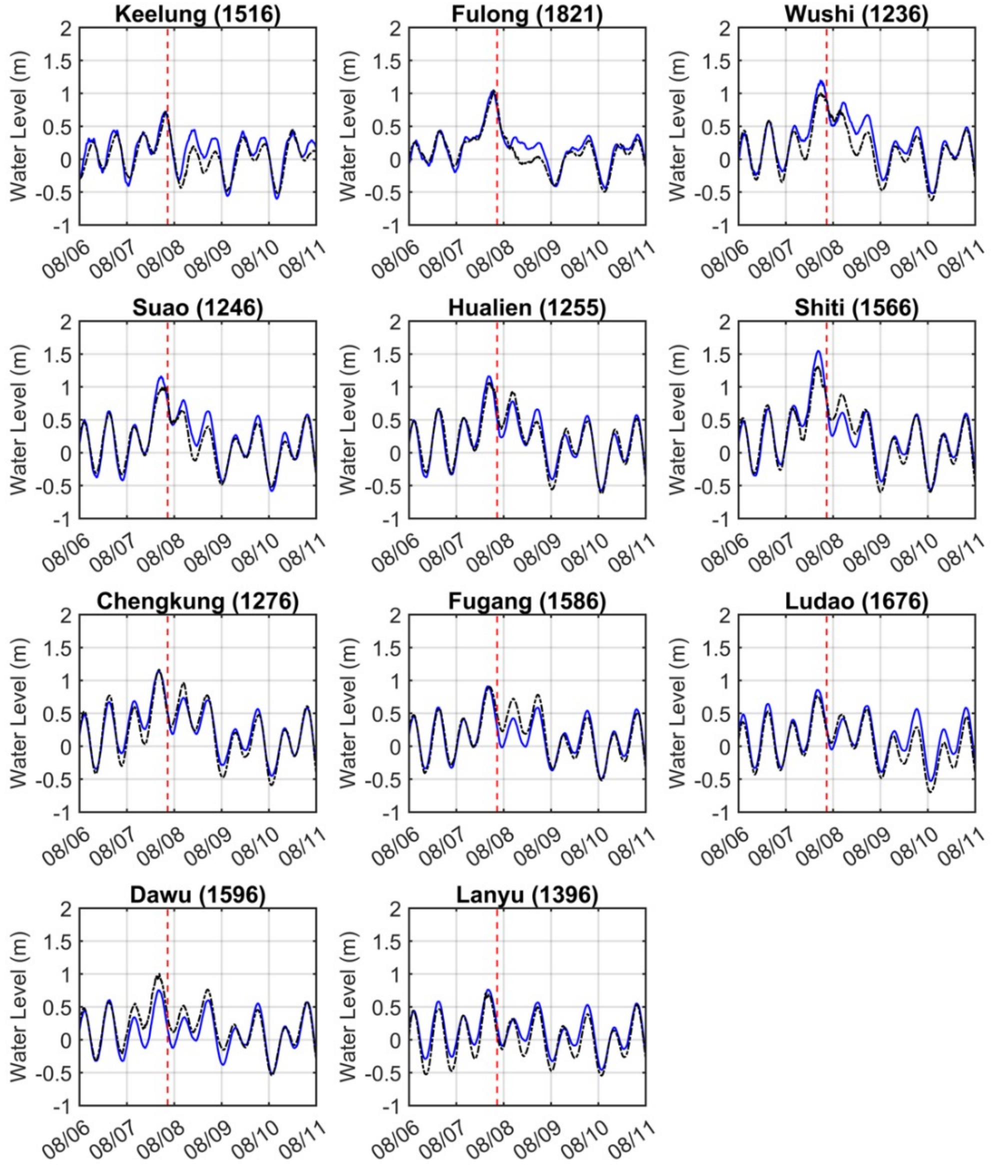


COMCOT-SURGE and SWAN adopt the same computational domains for model coupling (**one-way coupling**).

Numerical Modeling Results and Comparison

Blue – Numerical Results
Black – Observation Data

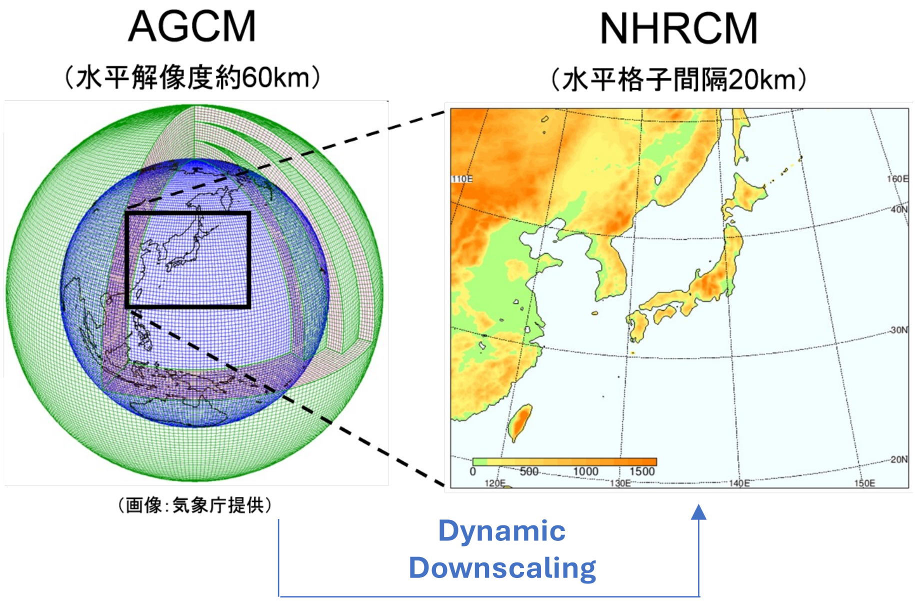


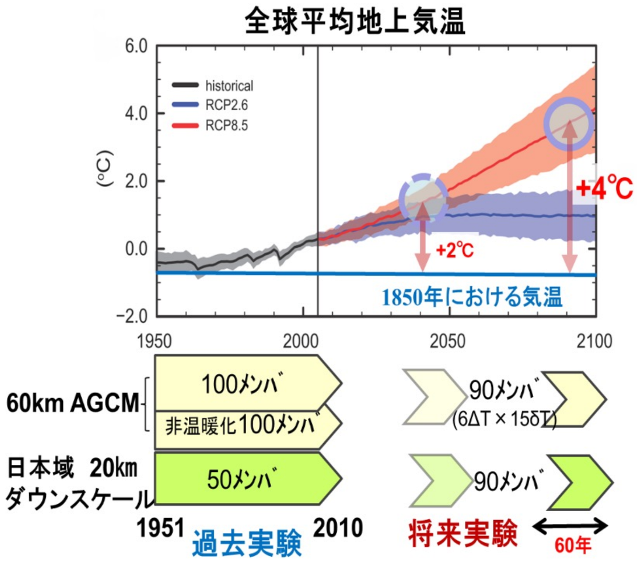


Tsai et al. (2025; Applied Ocean Research)

However, some challenges that we still have now.

d4PDF (Database for Policy Decision Making for Future Climate Change; Japan)





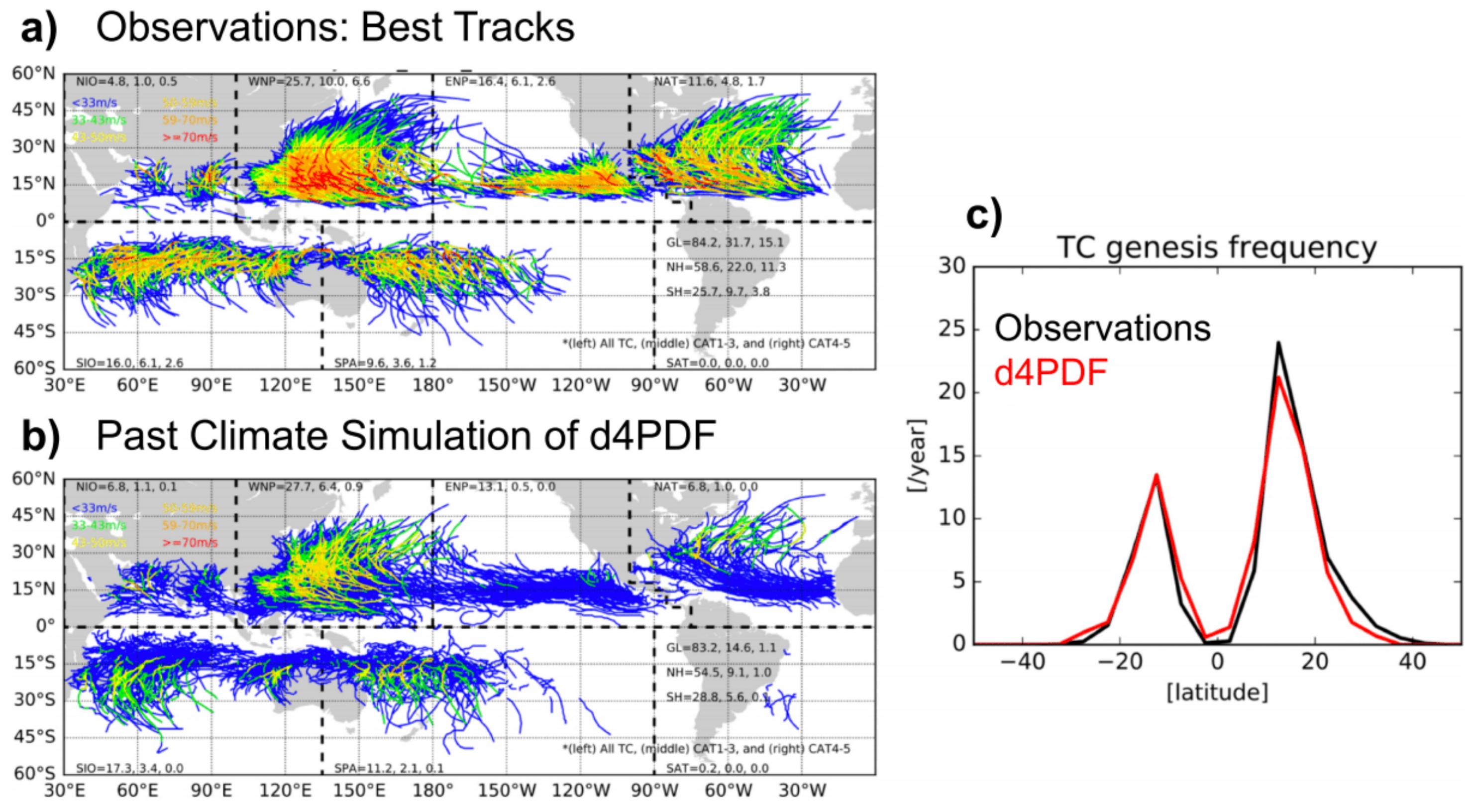


Fig. 6 a Observed (Knapp et al. 2010) and **b** simulated tropical cyclone trajectories. The simulation of d4PDF-G is of one member under the past climate condition. The trajectories are colored depending on wind speed. **c** Genesis frequencies of **a** and **b** as a function of latitude (Yoshida et al. 2017)

Four sets of experiments are performed by the AGCM;
- historical climate simulation: 1951-2010, **100 members**
- non-warming simulation: 1951-2010, **100 members**
- +2K future climate simulation: 2031-2090, **54 members**
- +4K future climate simulation: 2051-2110, **90 members**

Ishii & Mori. (2020). d4PDF: large-ensemble and high-resolution climate simulations for global warming risk assessment. Progress in Earth and Planetary Science.

Some challenges that we have

- Storm surge projection under **future climate change**.
  - Simulations are usually calculated for **50-100 years**.
  - Different climate change scenarios need to be considered for policy decision.

- Computational efficiency is a big issue!
  - Computation generally replies on super computers.
  - Workstations/clusters usually cannot handle the number of calculations.

- Simulations using **quantum computers** or **AI-hybrid techniques** may be one of solutions to enhance the simulation efficiency.

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Questions or Comments?

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