APAN Asia-Pacific Advanced Network

DMCC Disaster Mitigation Workshop

The Hazard Map from the Storm Surge Modeling and the Application on the 2013 Typhoon Haiyan

Yu-Lin Tsai[1], Tso-Ren Wu[1], Simon C. Lin[2],

Chuan-Yao Lin[3], Eric Yen[2], Denis F. Villorente[4], and ASTI Group

[1]Graduate Institute of Hydrological and Oceanic Sciences, NCU, Taiwan

[2]Academia Sinica Grid Computing, ASGC, Taiwan

[3]Research Center for Environmental Changes, RCEC, Taiwan

[4]Advanced Science and Technology Institute, ASTI , Philippines

國立中央大學 National Central University

水文與海洋科學研究所 Institute of Hydrological and Oceanic Sciences

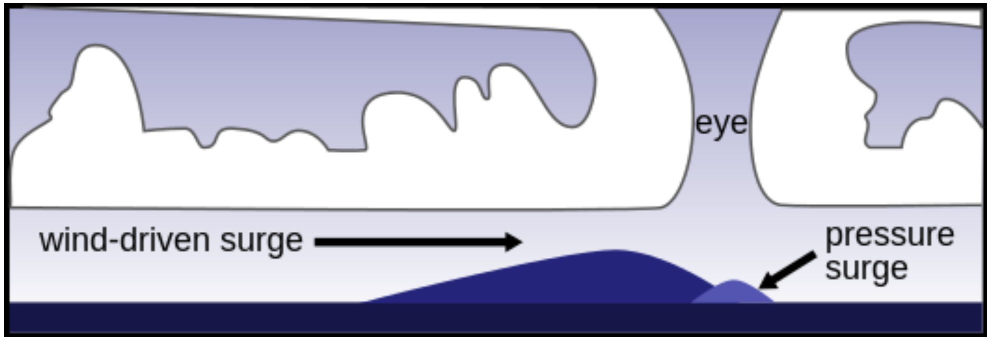
Tsunami Science Laboratory

ASGC TWGrid

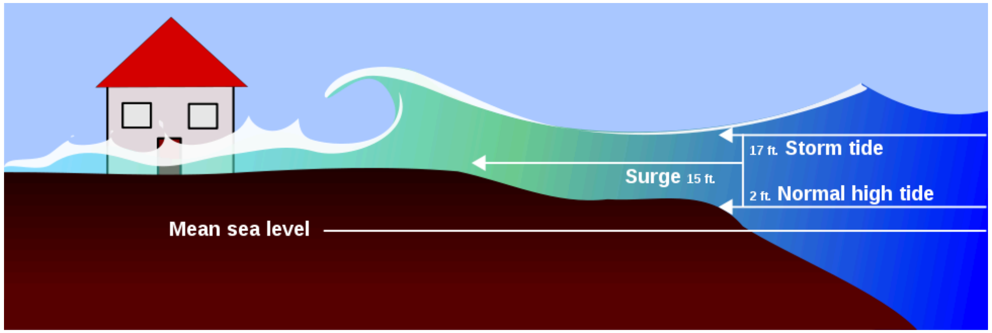
STORM SURGE

- Storm surge is a coastal flood of rising water commonly associated with low pressure weather systems (such as tropical cyclones, storms, typhoons, and hurricanes).

- The two main meteorological factors contributing to a storm surge are a long fetch of **winds** spiraling inward toward the storm, and a **low-pressure**-induced dome of water drawn up under and trailing the storm's center.



Sea Surface induced by typhoons (Wiki)



Tidal Effect with Storm Surges (Wiki)

Flooded by storm surge of Hurricane Katrina (2005) in the northwest New Orleans.

Inundation induced by Storm Surges

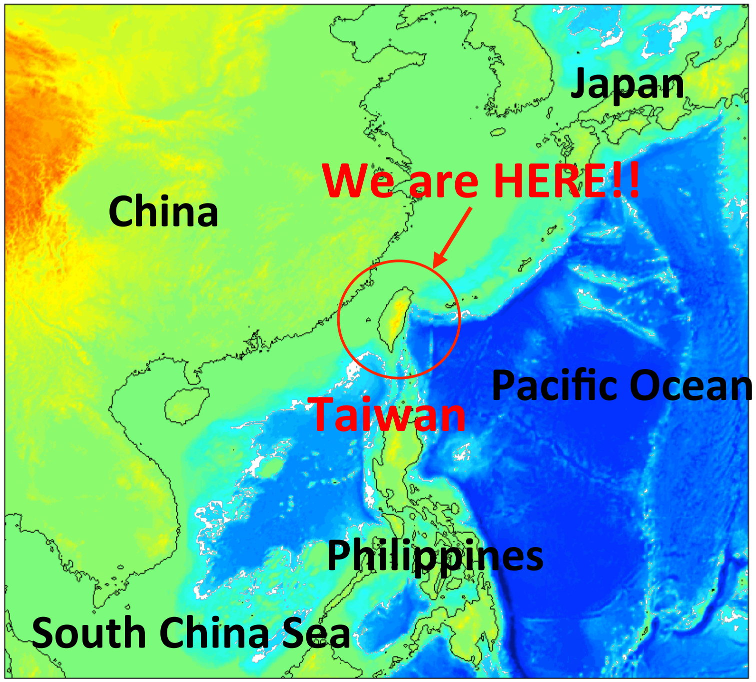
- *Destroy of homes and business*
- *Potential threat of coastal communities*
- *Damages of roads and bridges*

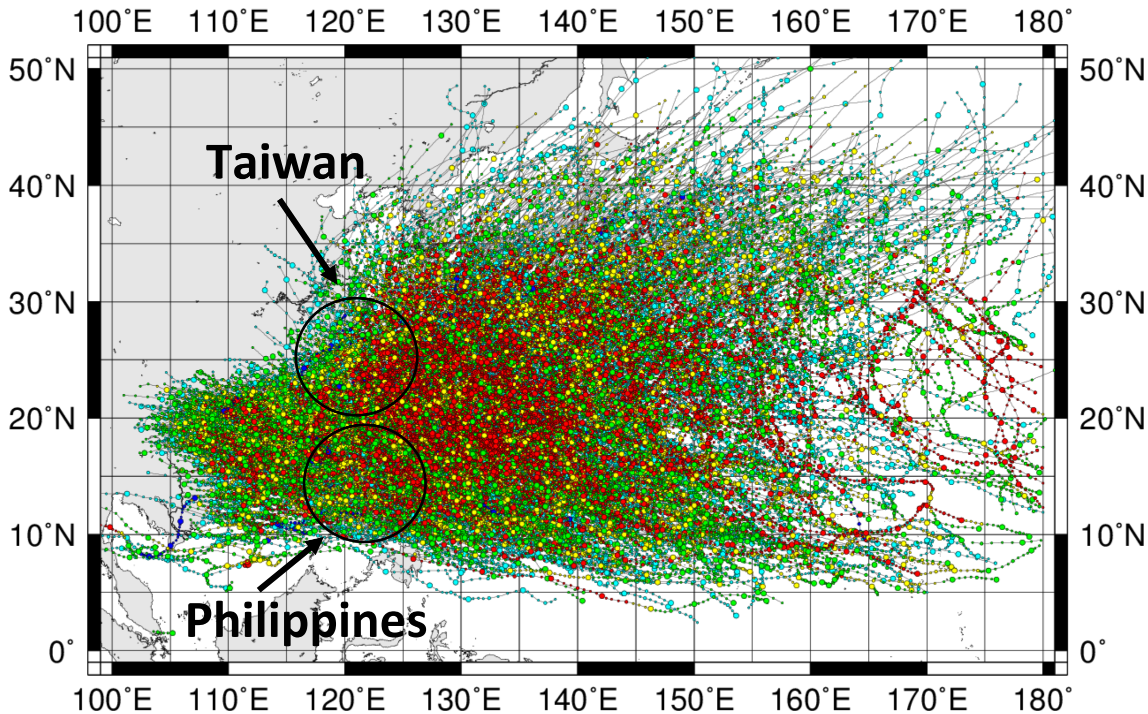
Where We Live

Views of inundated areas in New Orleans following breaking of the levees surrounding the city as the result of storm surge from Hurricane Katrina - 2005

Inundation induced by 2005 Hurricane Katrina.
(http://www.stormsurge.noaa.gov/)

Issues of Storm Surges in Taiwan Regions

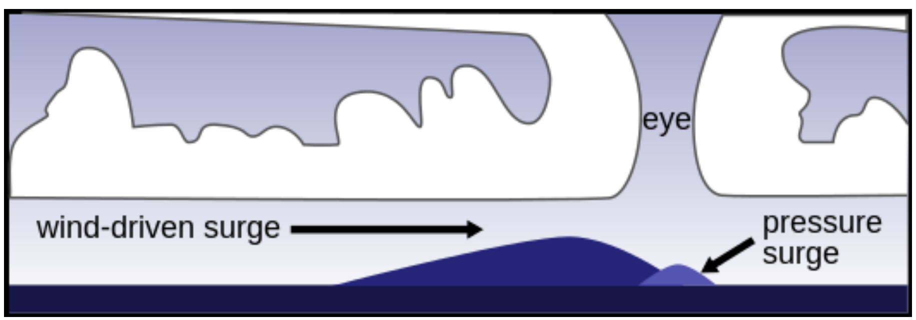




Tracks of all tropical cyclones in the northwestern Pacific Ocean between 1951 and 2014.

Our Goals for a Storm Surge Model (1)

- Spherical coordinate system with a large computational domain should be adopted to cover the complete life cycle of the typhoon .
- Nonlinear, bottom shear stress and shoaling effects should be all considered in nearshore and multi-scale wave propagation.
- Calculating inundation area with high-resolution topographic data.

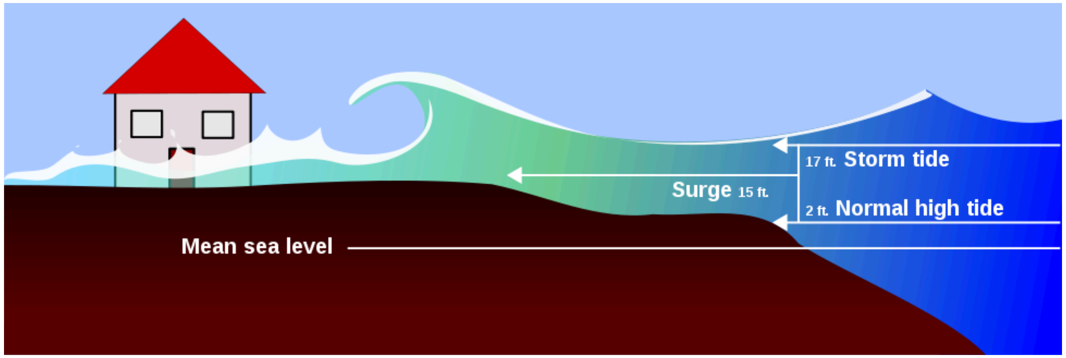


Sea Surface induced by typhoons (Wiki)

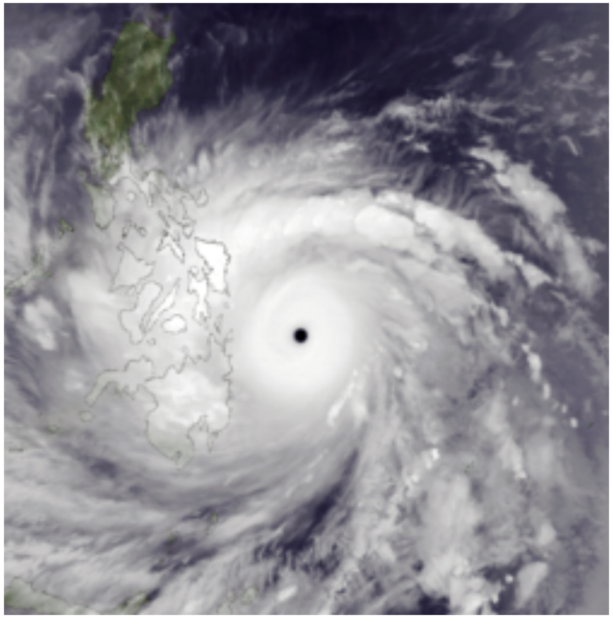
Storm Surge Propagation (NOAA)

Our Goals for a Storm Surge Model (2)

- Couple with the dynamic and regional-scale atmospheric model or idealized typhoon model (e.g. Holland Model or WRF Model).
- Couple with the global tide model (e.g. TPXO and Nao99b).
- High-speed efficiency for the early-warning system.
- Widely-validated.



Tidal Effect with Storm Surges (Wiki)



Meteorological Fields (Wiki)

The Introduction of Storm Surge Model
(COrnell Multi-grid COupled of Tsunami Model – Storm Surge)

Nonlinear Shallow Water Equations on the Spherical Coordinate

$$\frac{\partial \eta}{\partial t} + \frac{1}{R\cos\varphi}\left\{\frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}\left(\cos\varphi \cdot Q\right)\right\} = 0$$

$$\frac{\partial P}{\partial t} + \frac{1}{R\cos\varphi}\frac{\partial}{\partial \psi}\left(\frac{P^2}{H}\right) + \frac{1}{R}\frac{\partial}{\partial \varphi}\left(\frac{PQ}{H}\right) + \frac{gH}{R\cos\varphi}\frac{\partial \eta}{\partial \psi} - fQ + F_\psi^b = -\frac{H}{\rho_w R\cos\varphi}\frac{\partial P_a}{\partial \psi} + \frac{F_\psi^s}{\rho_w}$$

$$\frac{\partial Q}{\partial t} + \frac{1}{R\cos\varphi}\frac{\partial}{\partial \psi}\left(\frac{PQ}{H}\right) + \frac{1}{R}\frac{\partial}{\partial \varphi}\left(\frac{Q^2}{H}\right) + \frac{gH}{R}\frac{\partial \eta}{\partial \varphi} + fP + F_\varphi^b = -\frac{H}{\rho_w R}\frac{\partial P_a}{\partial \psi} + \frac{F_\varphi^s}{\rho_w}$$

- Solve shallow water equations on **both spherical and Cartesian coordinates**
- **Explicit leapfrog Finite Difference Method** for stable and high speed calculation
- **Multi/Nested-grid system** for multiple shallow water wave scales
- **Moving Boundary Scheme** for inundation
- **High-speed efficiency**

● Moving Boundary Scheme

Moving boundary scheme was also introduced in COMCOT to model the run-up and run-down. The instant "shoreline" is defined as the interface between a dry grid and wet grid and volume flux normal to the interface is assigned to zero.

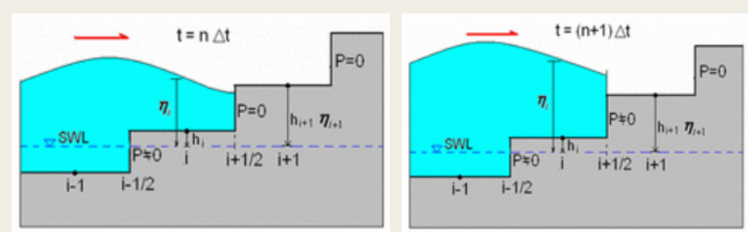


Fig.02 Moving Boundary Scheme

(1). Validation of Inundation Calculation

Compare with the solitary wave run-up Experiments (Synolakis, 1986 and 1987).

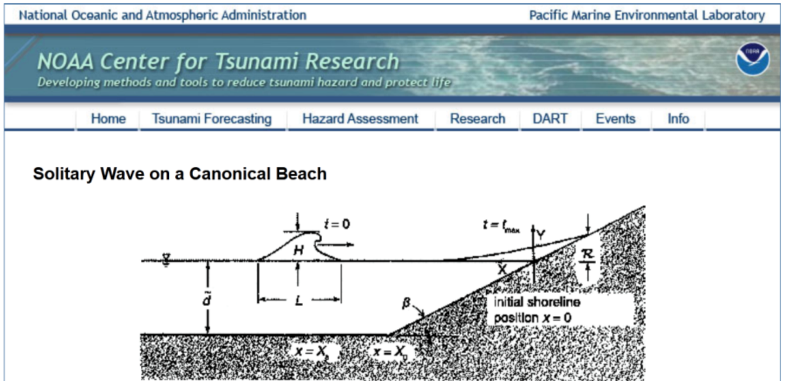
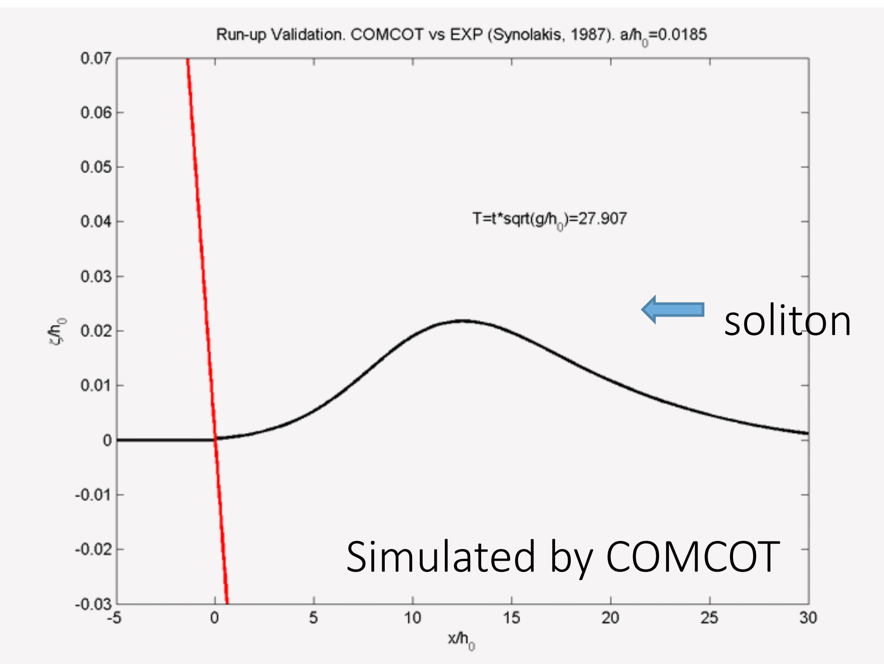
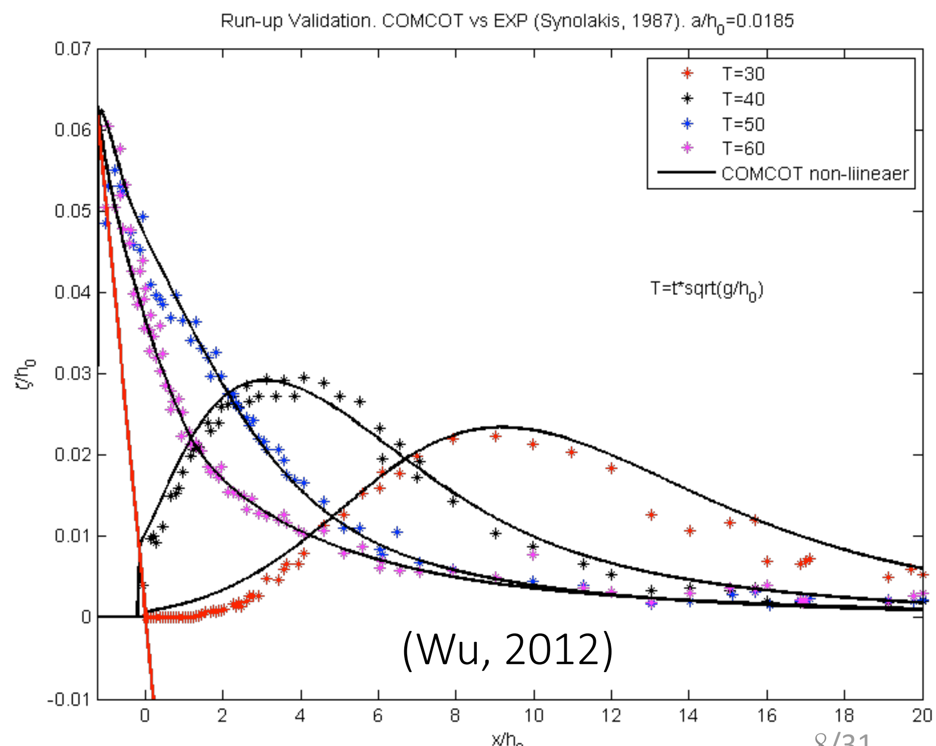


Figure 1: Definition sketch for canonical bathymetry, i.e., sloping beach connected to a constant-depth region.

Figure 2: Time evolution of H = 0.0185 initial wave over a sloping beach with $\cot\beta = 19.85$ from $t = 25$ to 65 with 10 increments. Constant depth-segment starts at $X_0 = 19.85$. While markers show experimental results of Synolakis (1986, 1987), solid lines show nonlinear analytical solution of Synolakis (1986, 1987) Experimental data is provided from $t = 30$ to 70 with 10 increments.

(from NOAA Official Website)





(2). Validation of Pressure Gradient

$$\frac{\partial P}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\psi}\left(\frac{P^2}{H}\right)+\frac{1}{R}\frac{\partial}{\partial\varphi}\left(\frac{PQ}{H}\right)+\frac{gH}{R\cos\varphi}\frac{\partial\eta}{\partial\psi}-fQ+F_\psi^b=-\frac{H}{\rho_w R\cos\varphi}\frac{\partial P_a}{\partial\psi}$$

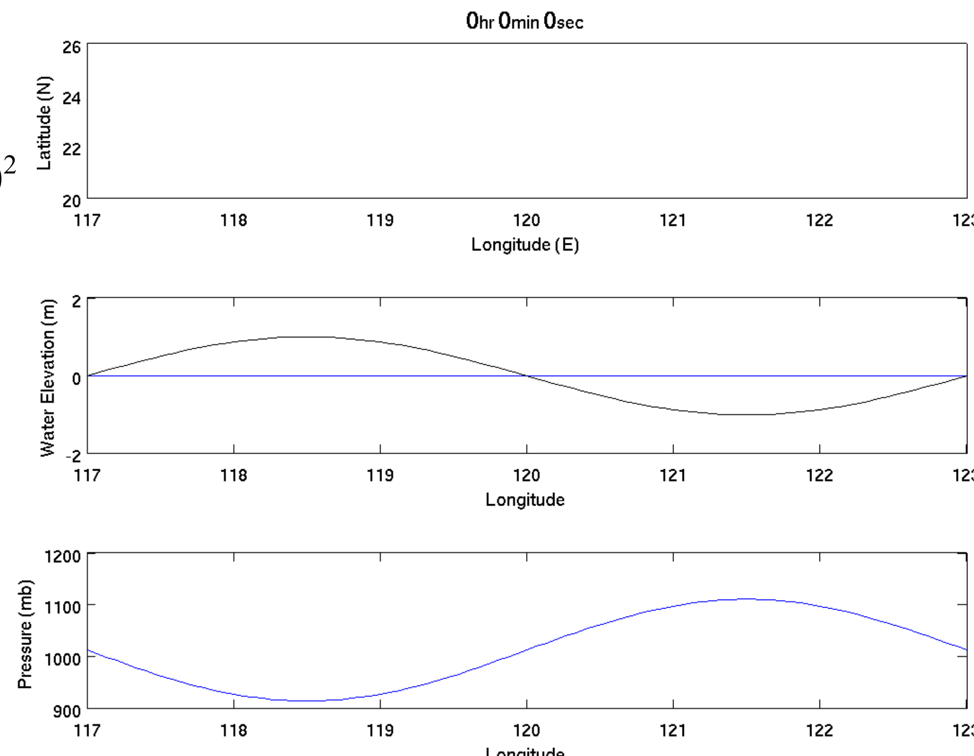
$$\longrightarrow \quad \frac{\partial P}{\partial t}+\frac{gH}{R\cos\varphi}\frac{\partial\eta}{\partial\psi}=-\frac{H}{\rho_w R\cos\psi}\frac{\partial P_a}{\partial\psi}$$

Steady-State Analytic Solution

$$P_a=-9800\cdot\sin\left[\frac{2\cdot\pi\left(\psi-\psi_1\right)}{\psi_2-\psi_1}\right]+1013.25\cdot 10^2$$

$$\partial\eta=-\frac{\partial P_a}{g\rho_w}=\sin\left[\frac{2\cdot\pi\left(\psi-\psi_1\right)}{\psi_2-\psi_1}\right]$$

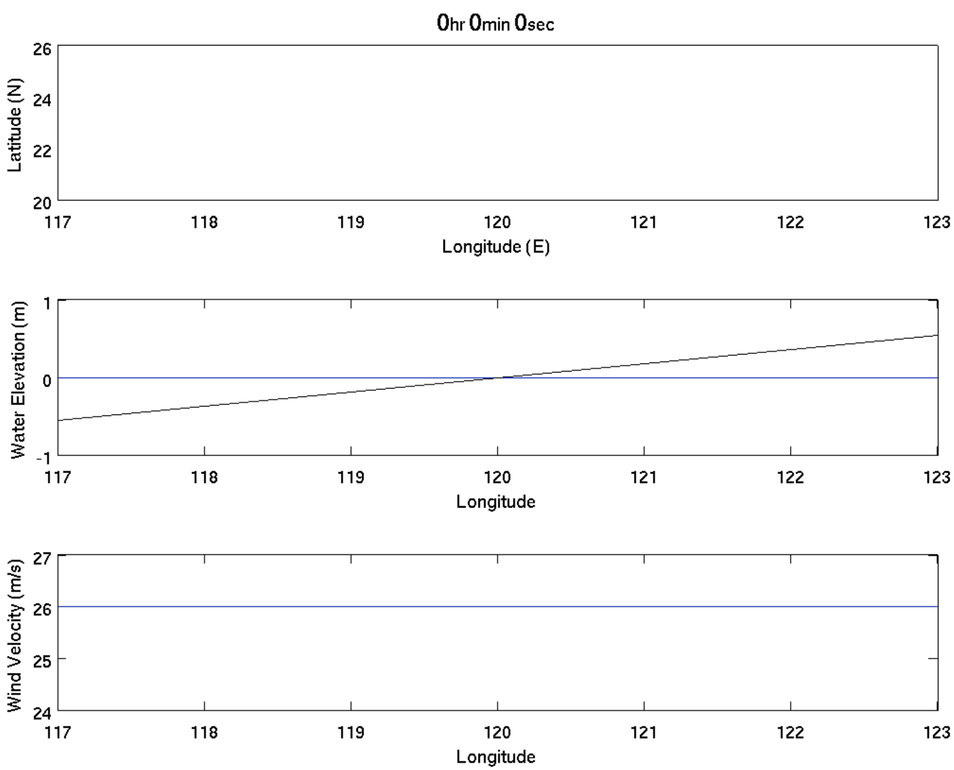
The simulated water elevation generated by the pressure gradient is in a good agreement with steady-state analytic solution.



(3). Validation of Wind Shear Stress

$$\frac{\partial P}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\psi}\left(\frac{P^2}{H}\right)+\frac{1}{R}\frac{\partial}{\partial\varphi}\left(\frac{PQ}{H}\right)+\frac{gH}{R\cos\varphi}\frac{\partial\eta}{\partial\psi}-fQ+F_\psi^b=\frac{F_\psi^s}{\rho_w}$$

$$\longrightarrow\quad \frac{\partial P}{\partial t}+\frac{gH}{R\cos\varphi}\frac{\partial\eta}{\partial\psi}=\frac{F_\psi^s}{\rho_w}$$



Steady-State Analytic Solution

$$\overrightarrow{V}_w=26(m/s)\qquad F_\psi^s=\rho_a C_d\left|\overrightarrow{V}_w\right|\overrightarrow{V}_w$$

$$\partial\eta=\rho_a C_d\left|\overrightarrow{V}_w\right|\overrightarrow{V}_w\cdot\frac{R\cdot\cos\varphi\cdot\partial\psi}{\rho_w\cdot gH}$$

$$=1.0992(\mathrm{m})$$

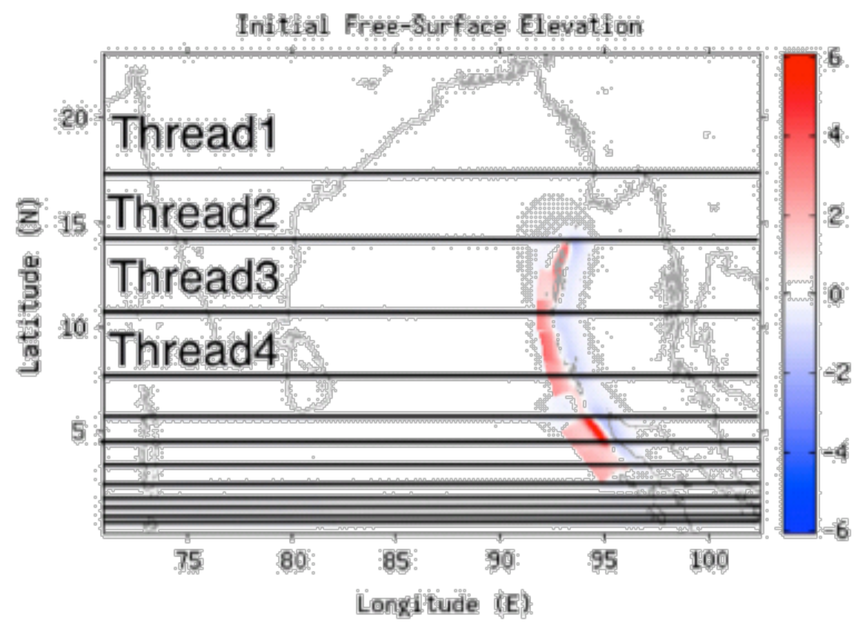
The simulated water elevation generated by the wind shear stress is in a good agreement with steady-state analytic solution.

(4). High-speed Calculation

Our model can finish 48 hrs forecast in 2 hours and be used for the operational system.

```
!$OMP PARALLEL DO PRIVATE(J,I,ZZZ,DD)
DO J=JS, JE
  DO I=IS, IE
    IF (L%H(I,J) .GT. ELMAX) THEN
      ZZZ = L%Z(I,J,1) - RX*(L%M(I,J,1)-L%M(I-1,J,1)) &
                - RY*(L%N(I,J,1)-L%N(I,J-1,1))
      ZZZ = ZZZ - (L%HT(I,J,2)-L%HT(I,J,1))
      IF (ABS(ZZZ) .LT. EPS) ZZZ = 0.0
      DD = ZZZ + L%H(I,J)
      ...
    ELSE
      ...
    END IF
  END DO
END DO
!$OMP PARALLEL DO
```

Parallel Computing on Multi Cores.



Dynamic resources sharing.

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Review

Development of a tsunami early warning system for the South China Sea

Simon C. Lin[a], Tso-Ren Wu[c,*], Eric Yen[b], Hsin-Yen Chen[b], John Hsu[a], Yu-Lin Tsai[c], Chun-Juei Lee[c], Philip, L.-F. Liu[c,d]

[a] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
[b] Academia Sinica Grid Computing Centre, Taipei 11529, Taiwan
[c] Institute of Hydrological & Oceanic Sciences, National Central University, Jhongli 32001, Taiwan
[d] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

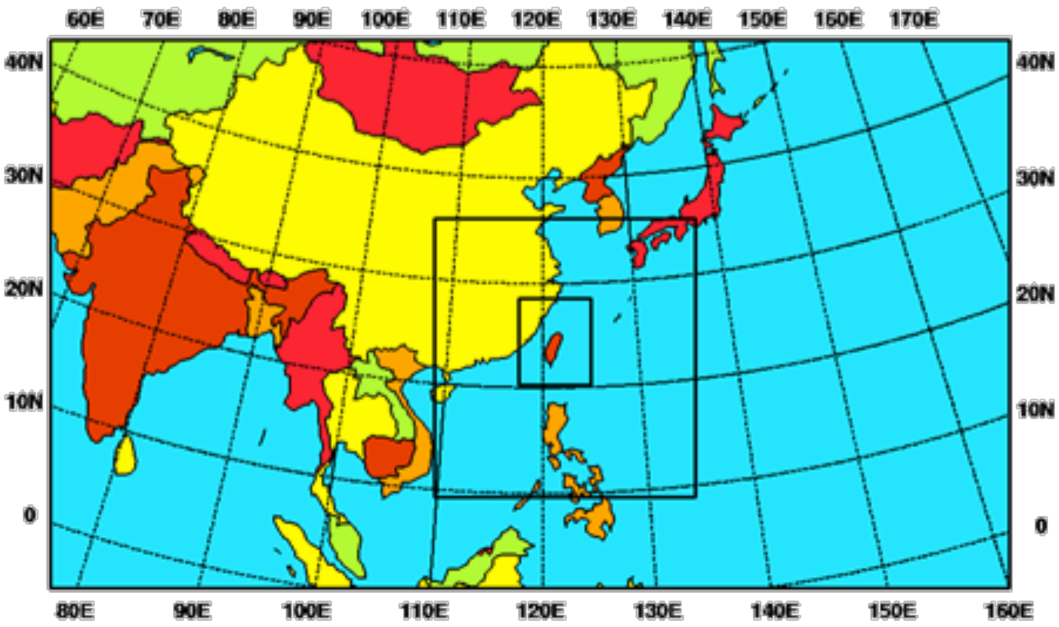
The results has been published on Ocean Engineering (Lin et al., 2015).

(5). Couple with the Atmospheric Model

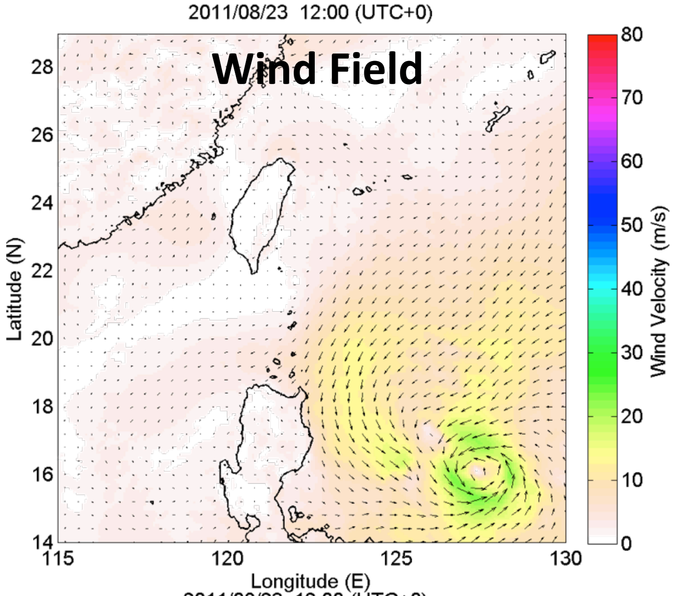
WRF (Weather Research and Forecasting Model)

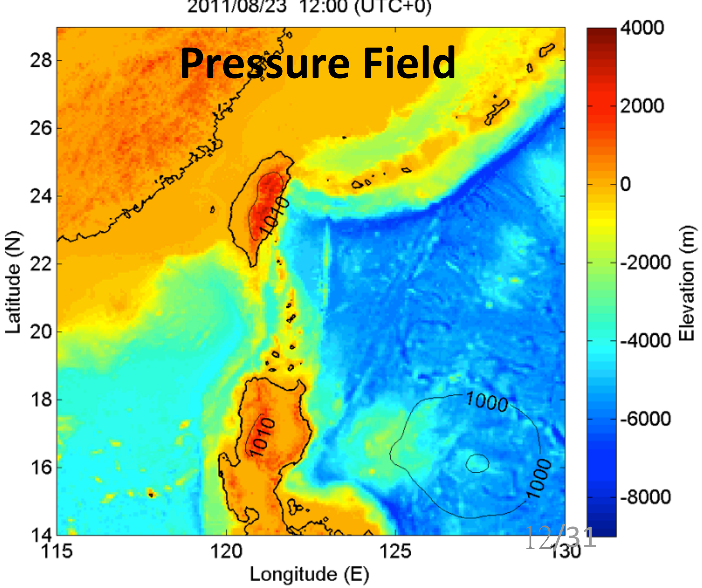
- WRF model is an atmospheric model adopted for operational forecasts by Central Weather Bureau in Taiwan.

- The WRF model will start its simulation per 6 hours in a day at 00, 06, 12 and 18 UTC time respectively.



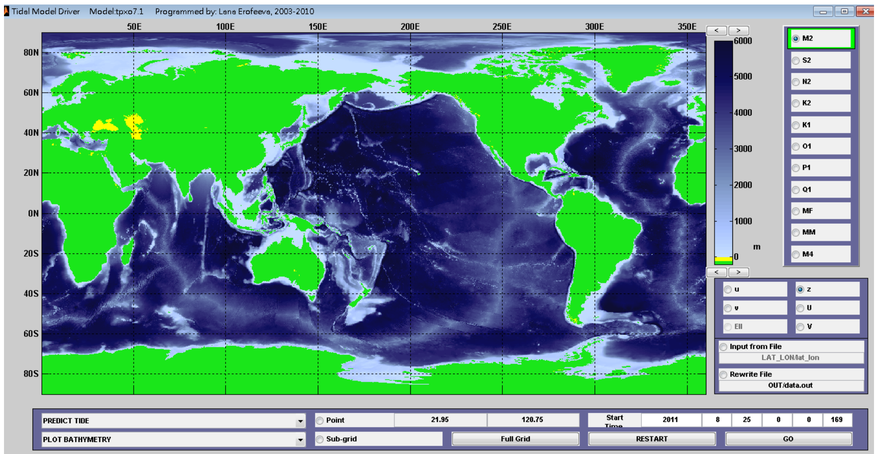
Computational Domain (CWB)





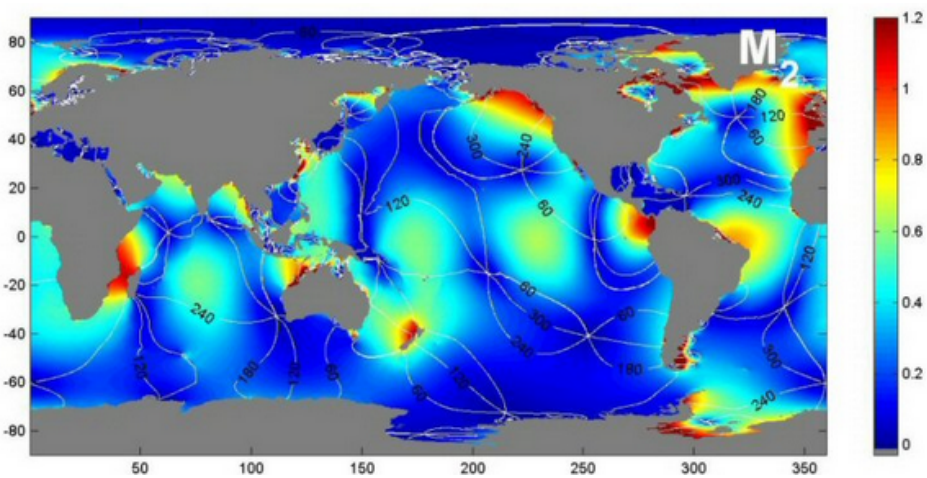
(6). Couple with Global Tide TPXO Model

(TOPEX/POSEIDON Global Tidal Model)



User Interface of TPXO

The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf,Mm) and 3 non-linear (M4, MS4, MN4) harmonic constituents.



TPXO can provide tidal information, like M2.

A TOPEX/POSEIDON global tidal model (TPXO.2) and barotropic tidal currents determined from long-range acoustic transmissions

Brian D. Dushaw[1], Gary D. Egbert[2], Peter F. Worcester[3], Bruce D. Cornuelle[3], Bruce M. Howe[1] and Kurt Metzger[4]

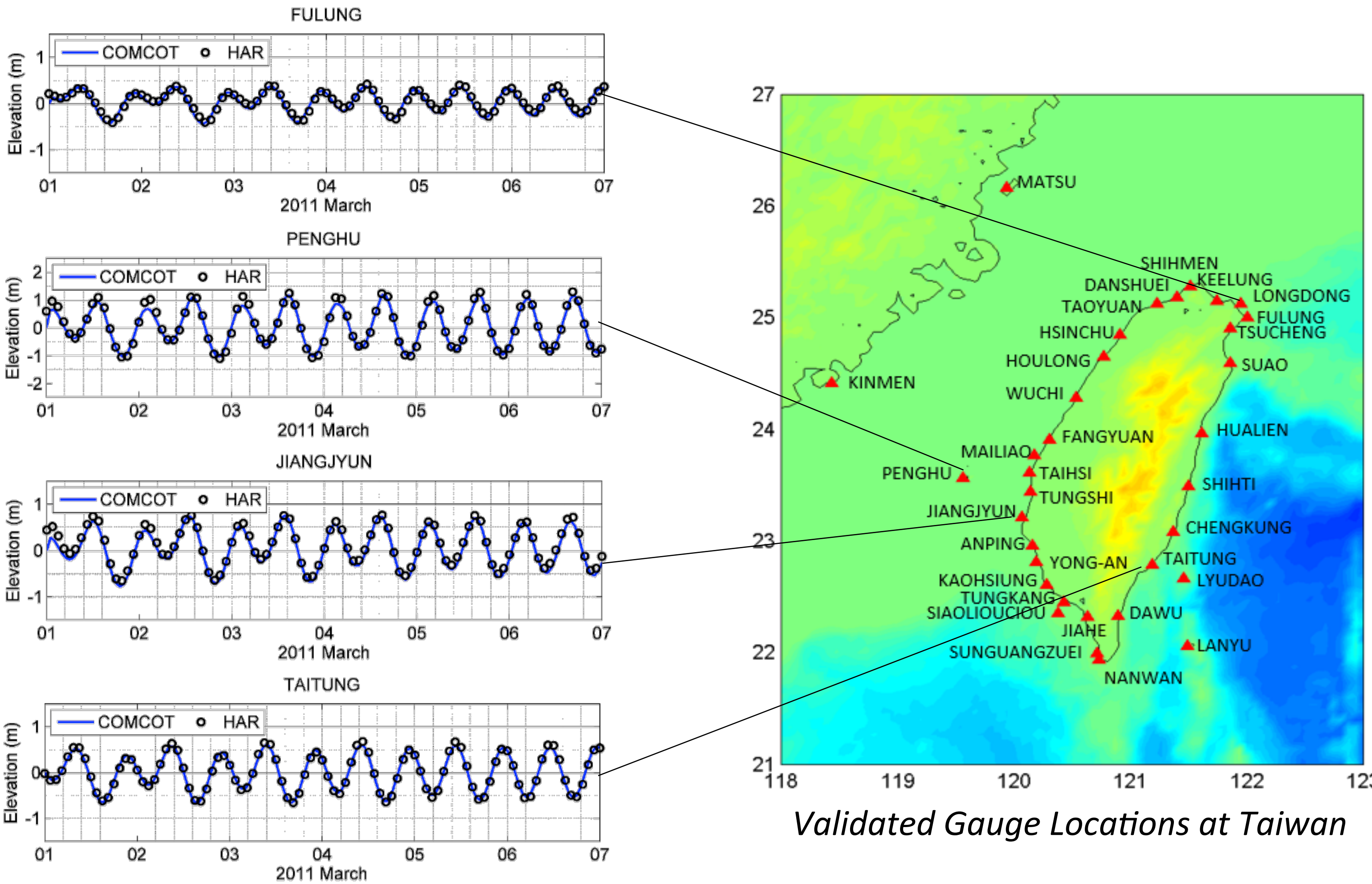
[1]*Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, Seattle, WA, U.S.A.*
[2]*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, U.S.A.*
[3]*Scripps Institution of Oceanography, La Jolla, CA, U.S.A.*
[4]*Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, U.S.A.*

Abstract – Tidal currents derived from the TPXO.2 global tidal model of Egbert, Bennett, and Foreman are compared with those determined from long-range reciprocal acoustic transmissions. Amplitudes and phases of tidal constituents in the western North Atlantic are derived from acoustic data obtained in 1991–1992 using a pentagonal array of transceivers. Small, spatially coherent differences between the measured and modeled tidal harmonic constants mostly result from smoothing assumptions made in the model and errors caused in the model currents by complicated topography to the southwest of the acoustical array. Acoustically measured harmonic constants (amplitude, phase) of M_2 tidal vorticity ($3–8 \times 10^{-9}$ s^{-1}, 210–310°) agree with those derived from the TPXO.2 model ($2–5 \times 10^{-9}$ s^{-1}, 250–300°), whereas harmonic constants of about ($1–2 \times 10^{-9}$ s^{-1}, 350–360°) are theoretically expected from the equations of motion. Harmonic constants in the North Pacific Ocean are determined using acoustic data from a triangular transceiver array deployed in 1987. These constants are consistent with those given by the TPXO.2 tidal model within the uncertainties. Tidal current harmonic constants determined from current meters do not generally provide a critical test of tidal models. The tidal currents have been estimated to high accuracy using long-range reciprocal acoustic transmissions; these estimates will be useful constraints on future global tidal models.

(Dushaw et al., 1997)

(7). High-Accuracy Tide Validation

The bias is smaller than 0.1 m and root mean square is smaller than 0.6 m.

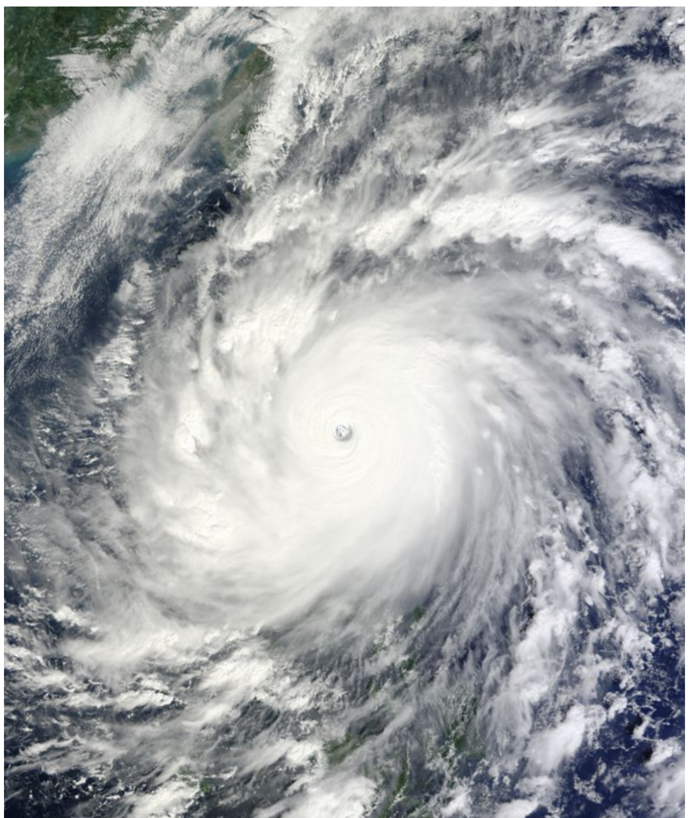


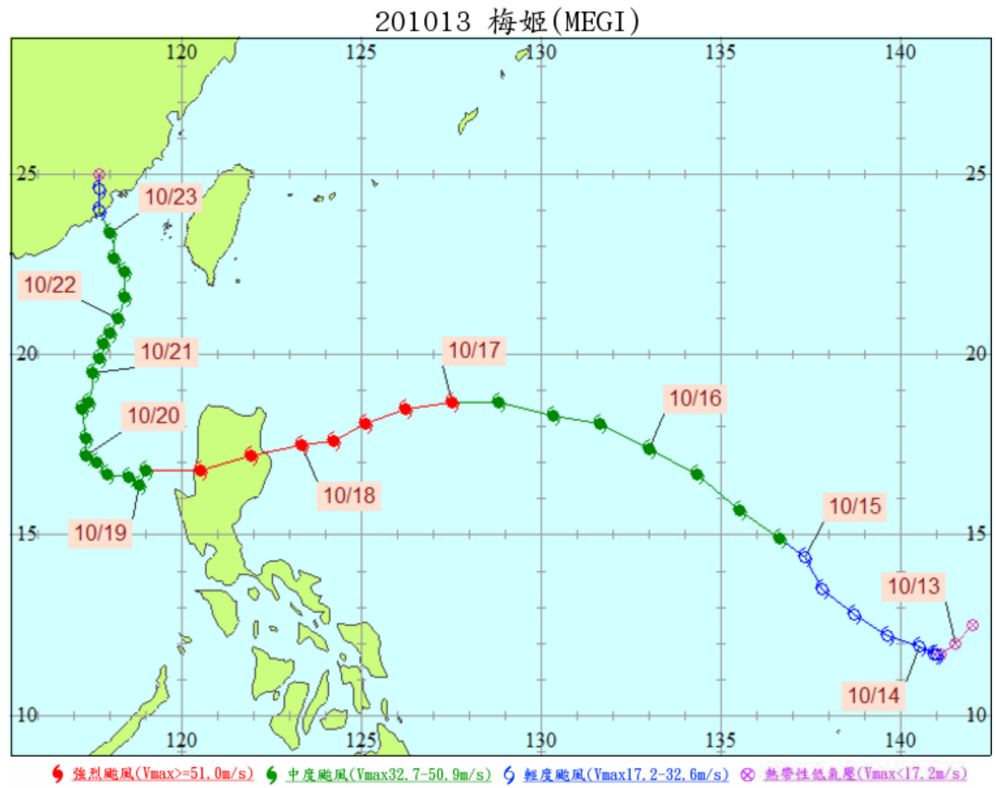
Validated Gauge Locations at Taiwan

The observed data and harmonic data are provided by CWB (Taiwan).

Model Validation - 2010 Typhoon Megi

- Severe Typhoon Megi was the strongest typhoon in 2010 and generated the destructive storm surges at Philippines. After Megi passed through Philippines, it turned northward to China and the Taiwan Strait. The typhoon route of Megi was defined as track type 9 by CWB.

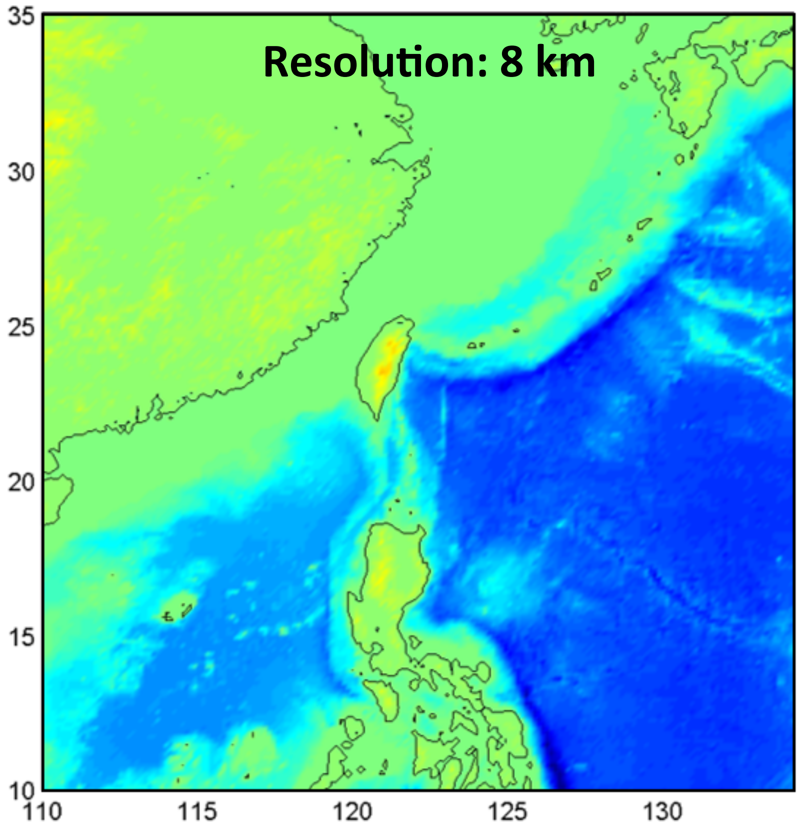




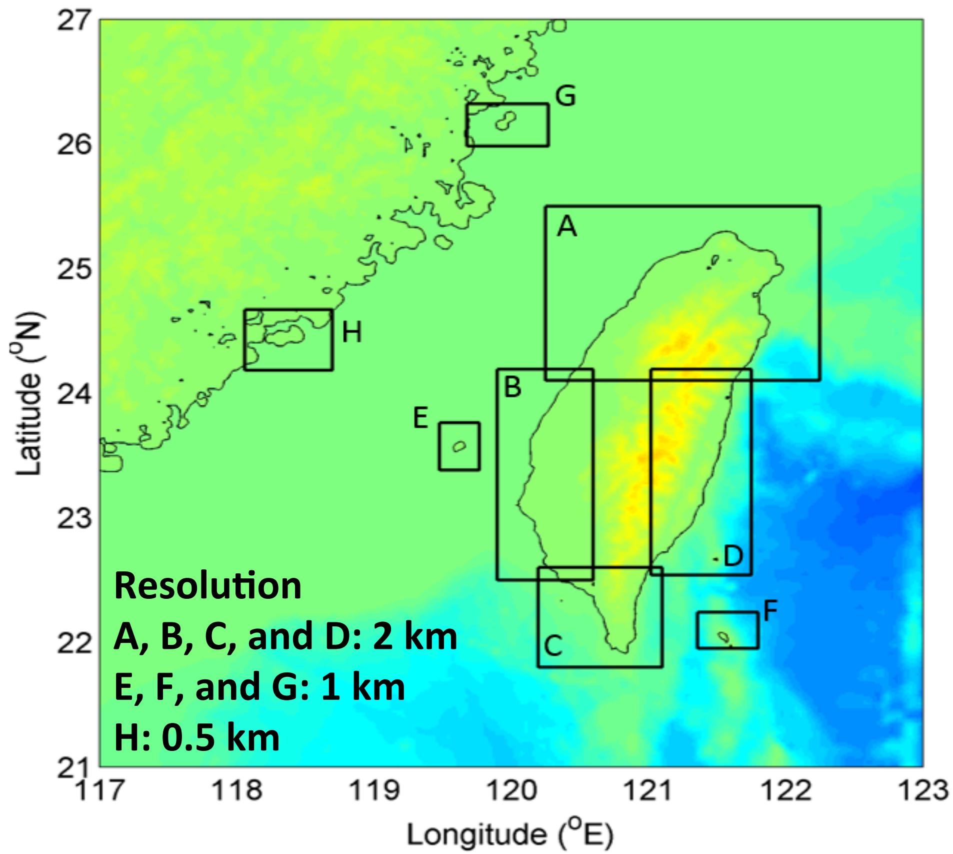
Copyright @ CWB Typhoon Database

Nested Domains for Taiwan Regions

LAYER 01



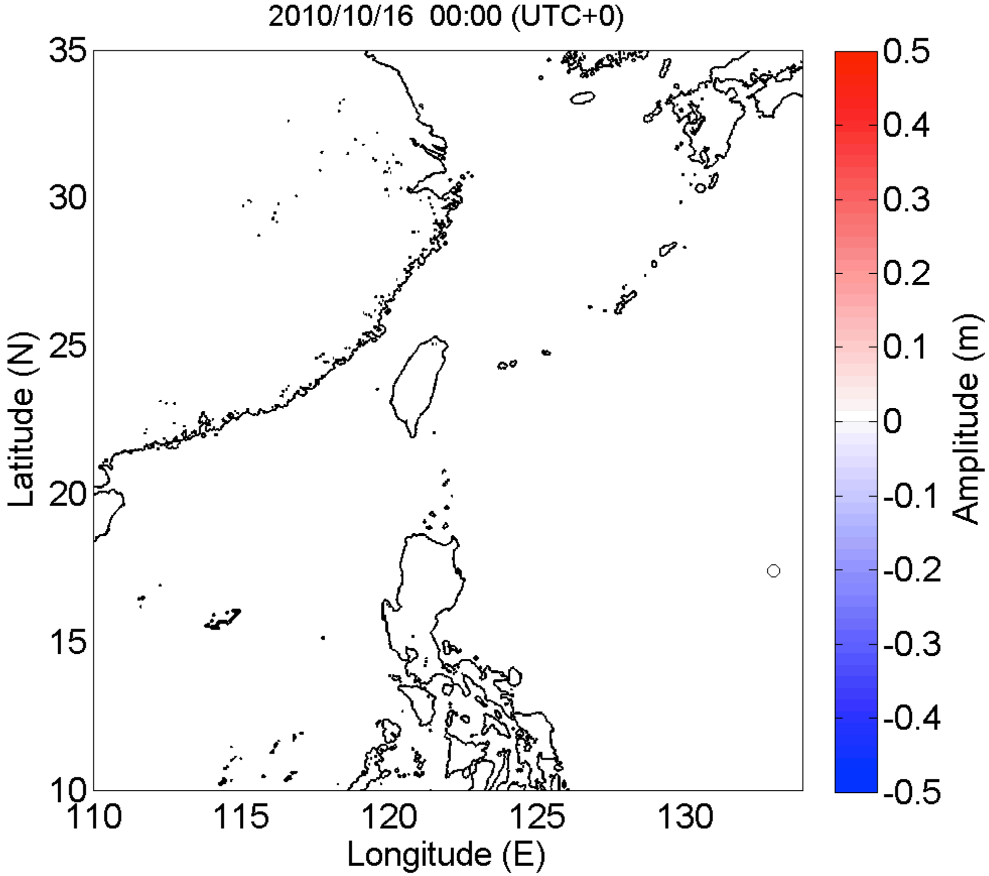
LAYER 02

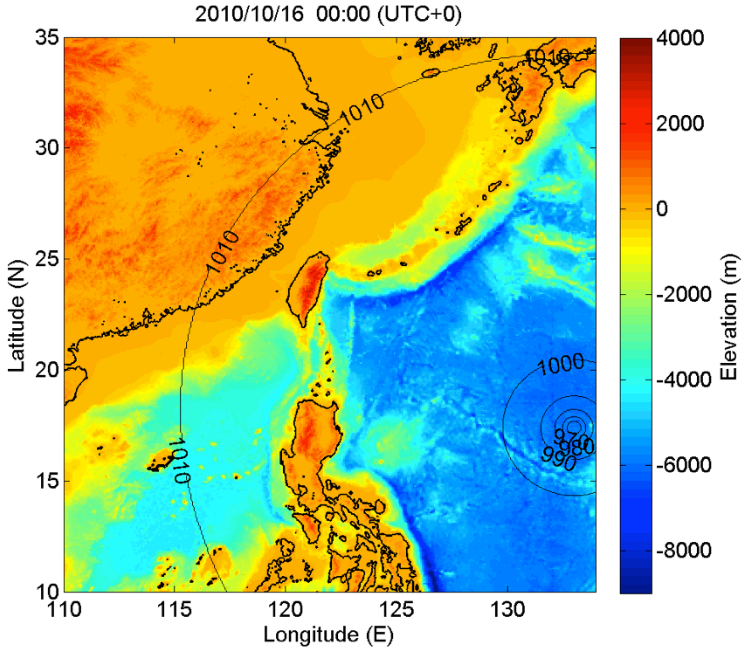


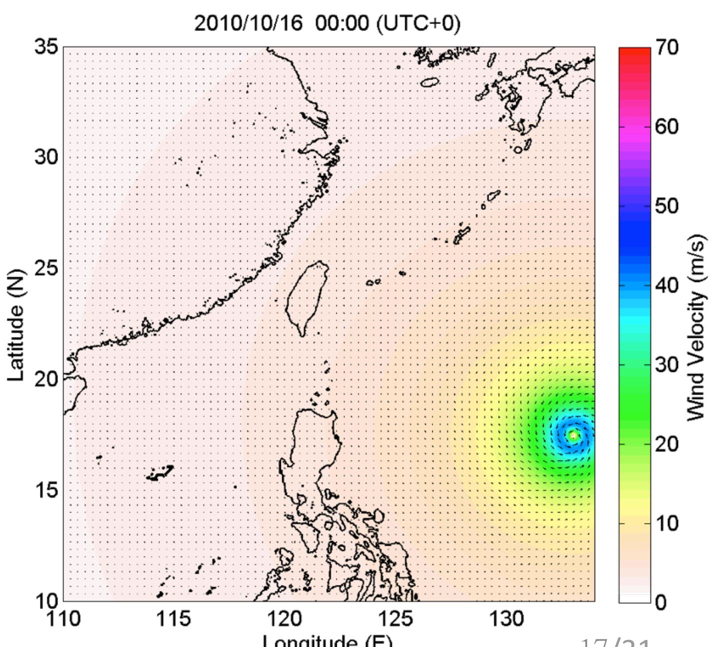
- *Layer 01 can cover the complete typhoon life cycle and the full storm surge propagation.*
- *Layer 02 can include the offshore hydrodynamic progresses of storm surge on the fine mesh domains and couple with tidal effect.*

Simulation of Typhoon Megi

2010.10.15 00:00 – 2010.10.23 12:00 (UTC+0)



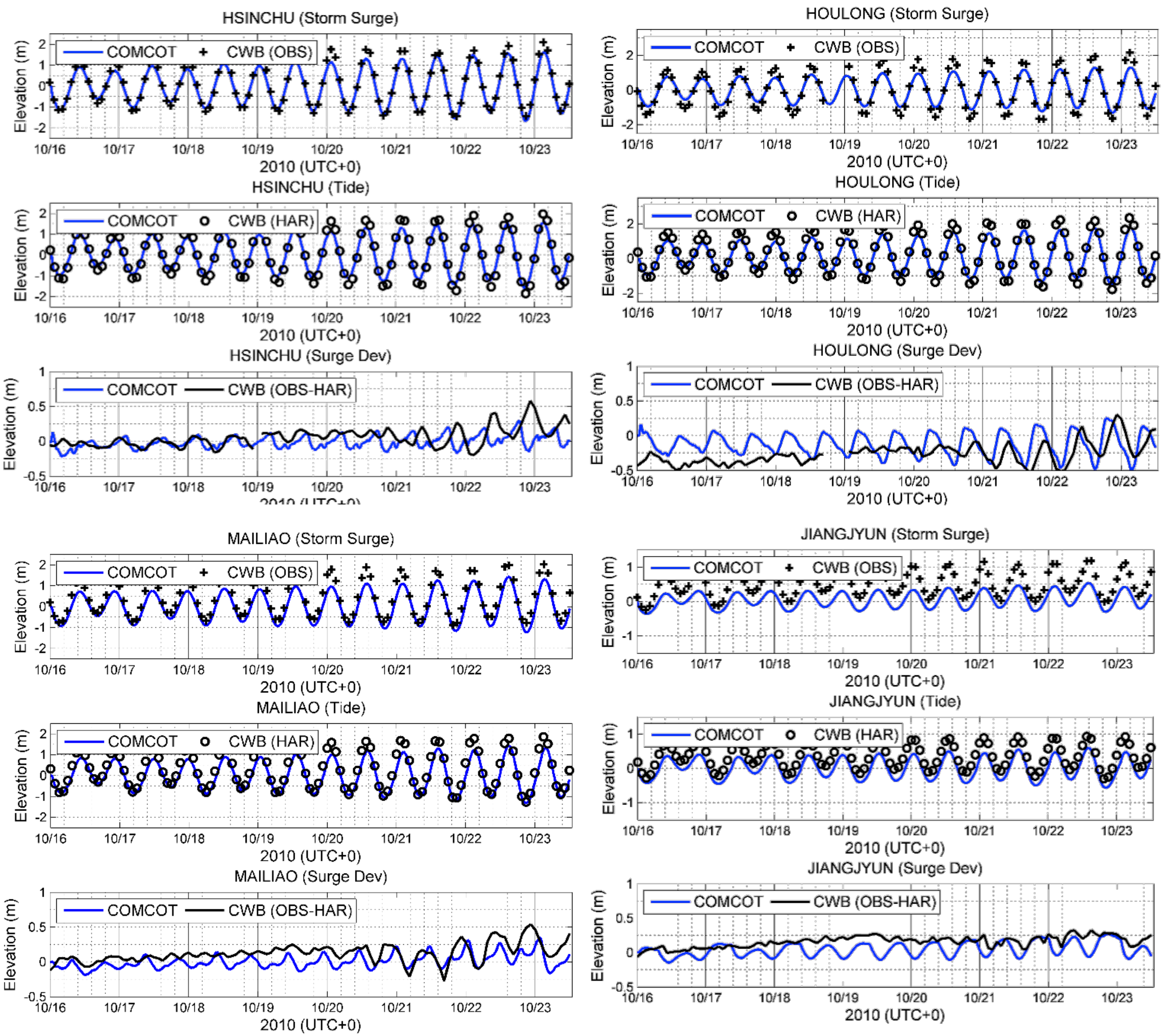


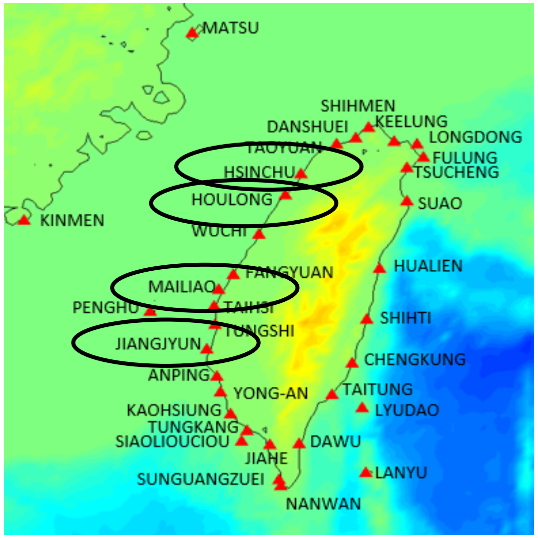


The results are storm surge, pressure field and wind field.

Gauge Comparison

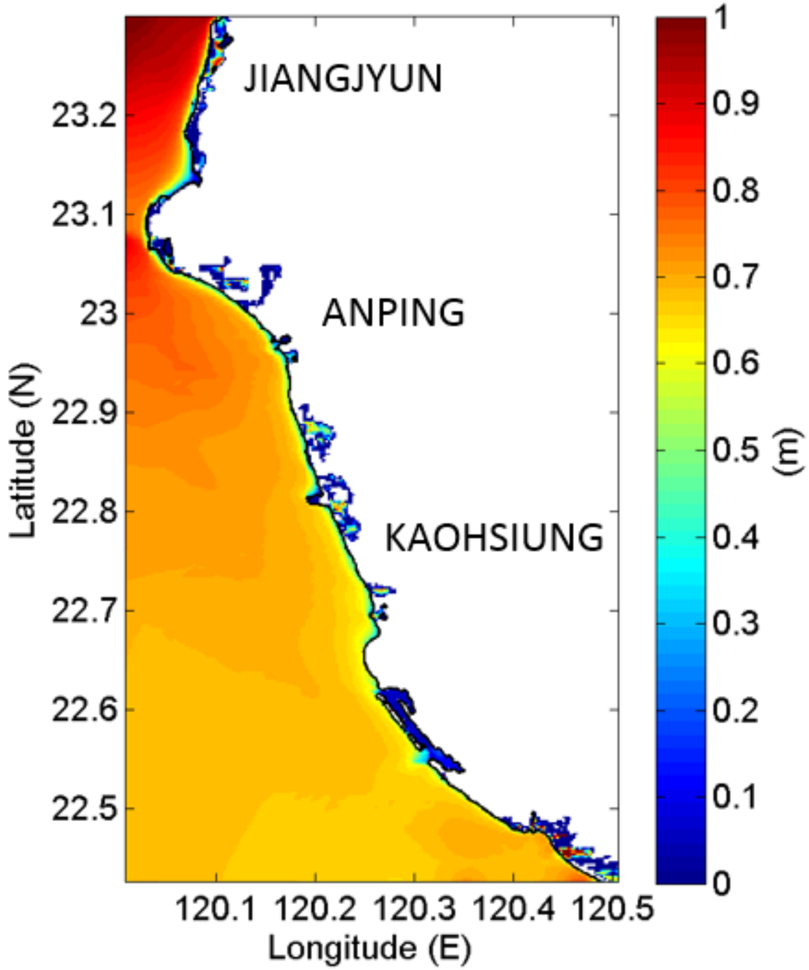
2010.10.15 00:00 – 2010.10.23 12:00 (UTC+0)



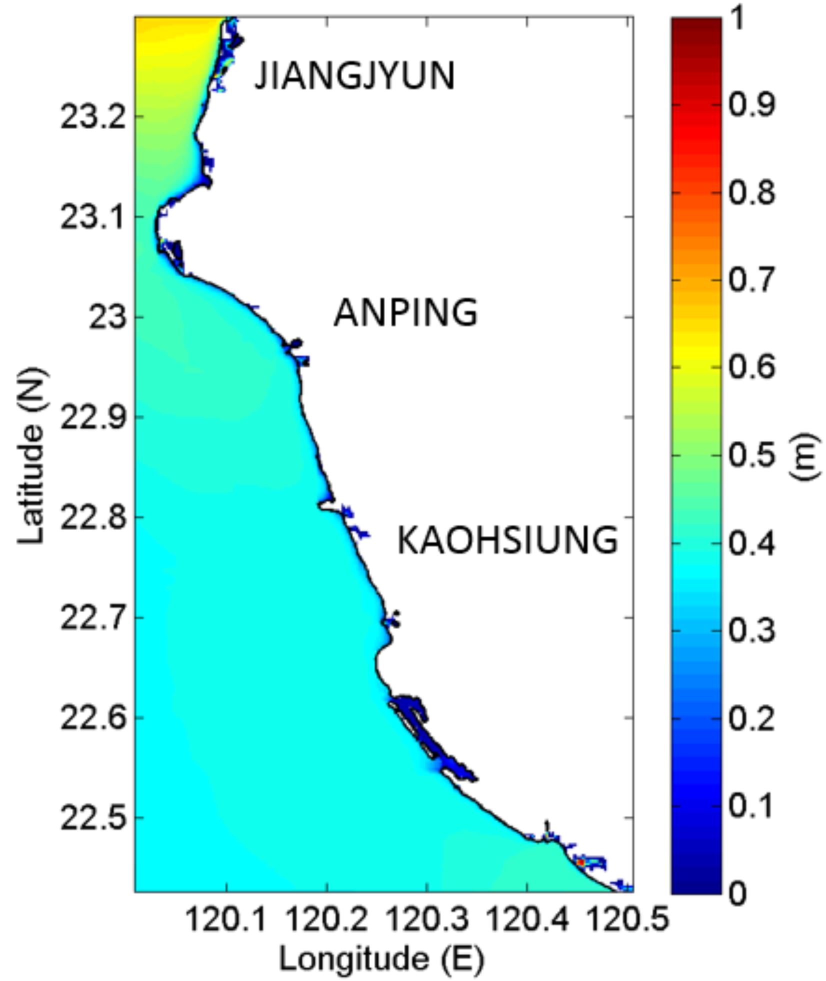


Inundation Area and Maximum Surge Height

Storm Tides

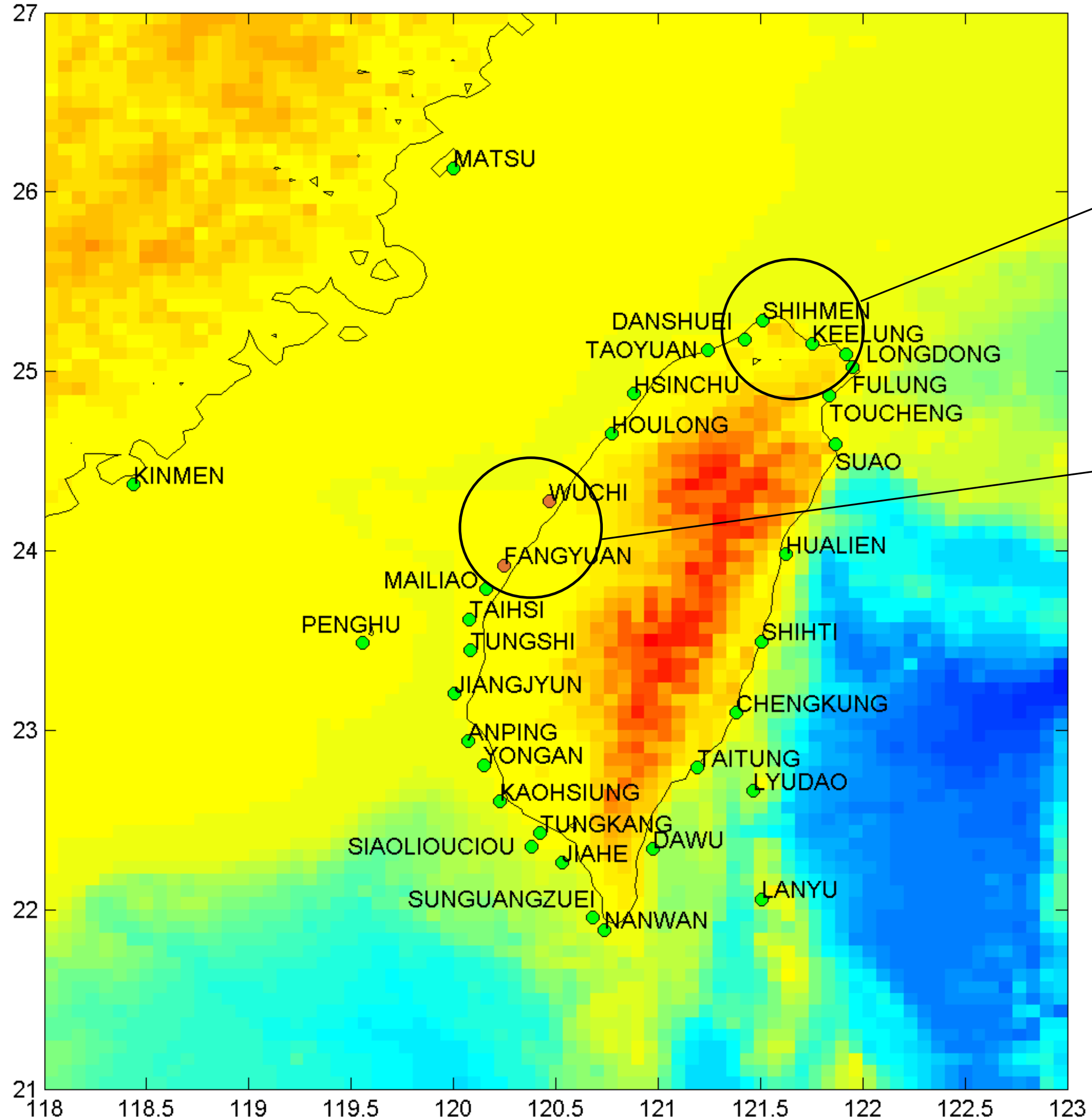


Tides



The simulated results on the resolution of 200 meters indicated that Jiangjyun, Anping and Kaohsiung would be potentially surge-flooded areas.

Model Product on Surge-Inundated Warns



The **Greens** indicate that these regions are safe areas and without the potential surge-inundated warns.

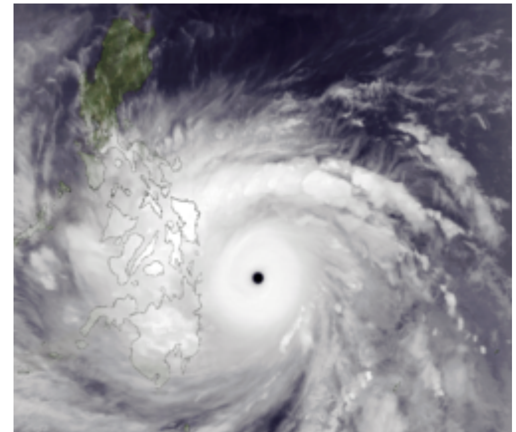
The **Oranges** indicate that these regions are under the potential threat of surge inundation.

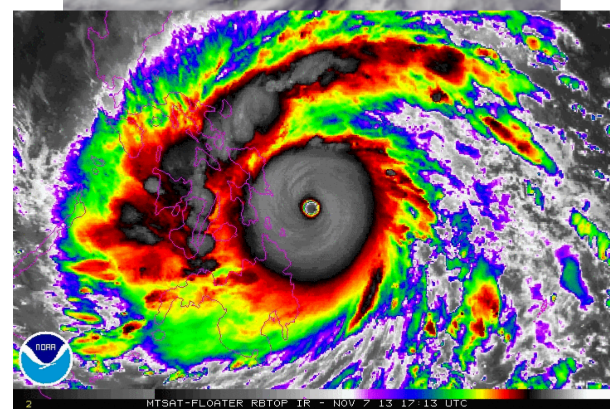
- The surge-inundated warns will be determined automatically by the dry-wet-cell treatment.
- If potentially-inundated areas are calculated, the signs will change the colors from green to orange.

2013 Super Typhoon Haiyan in the Philippines

Typhoon Life Cycle: November 3rd –November 11th

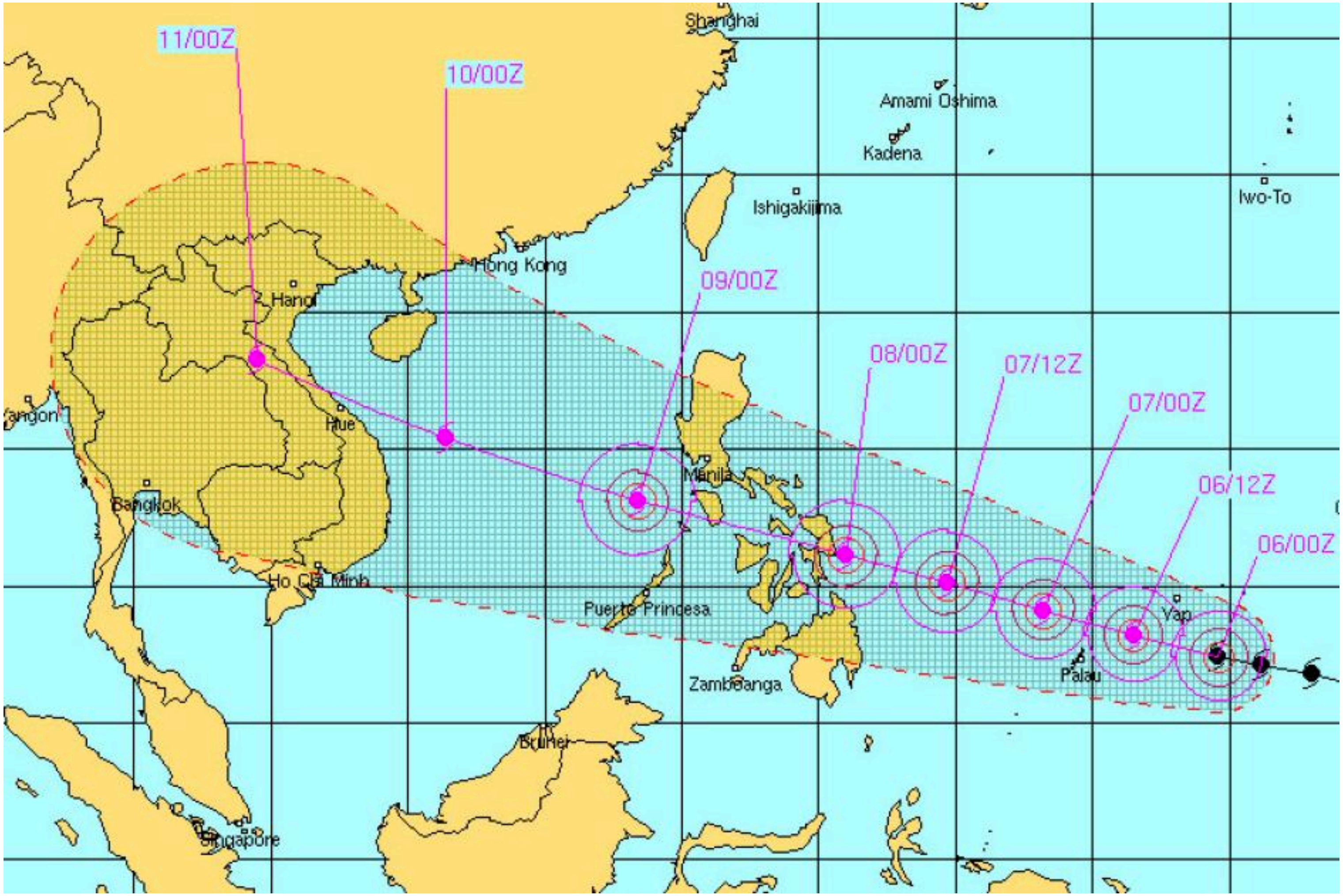
*Typhoon Haiyan: '**It was like the end of the world**'.*





Typhoon Haiyan was the strongest typhoon than tropical cyclones ever recorded, and devastated portions of Southeast Asia, particularly the Philippines, in early-November 2013.

The Track of 2013 Typhoon Haiyan



(Copyright: The US Joint Typhoon Warning Center)

San Juanico Bridge

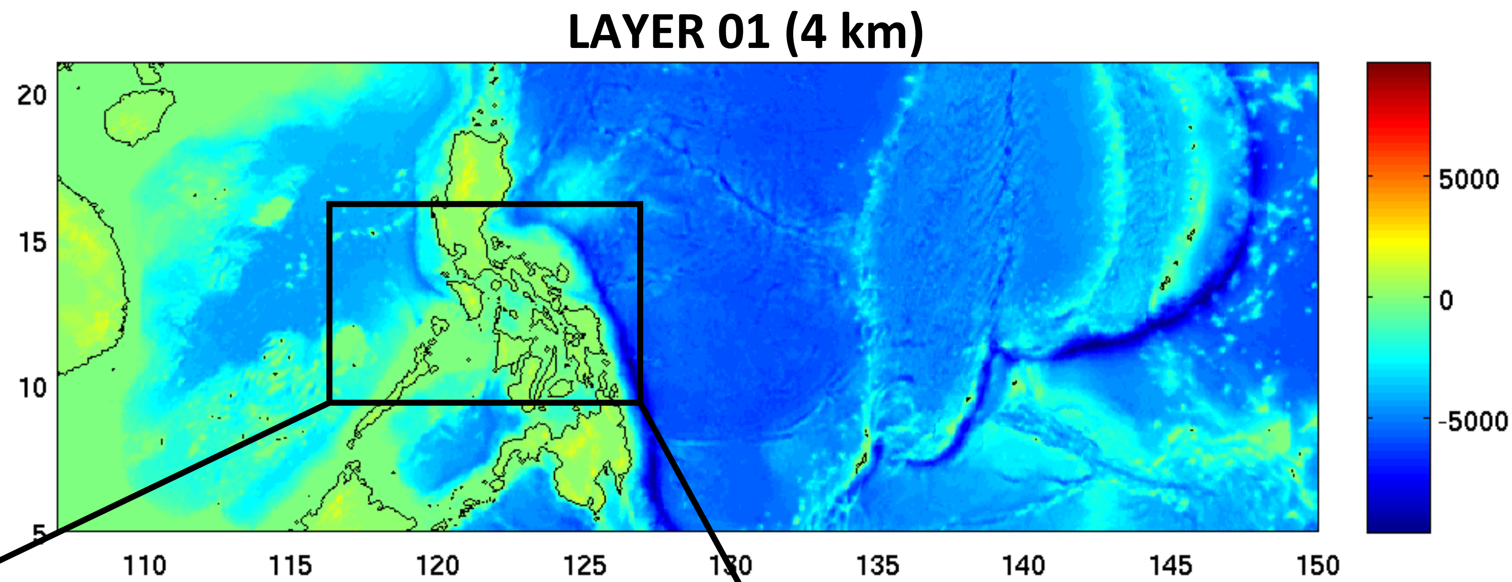
Tagpuro

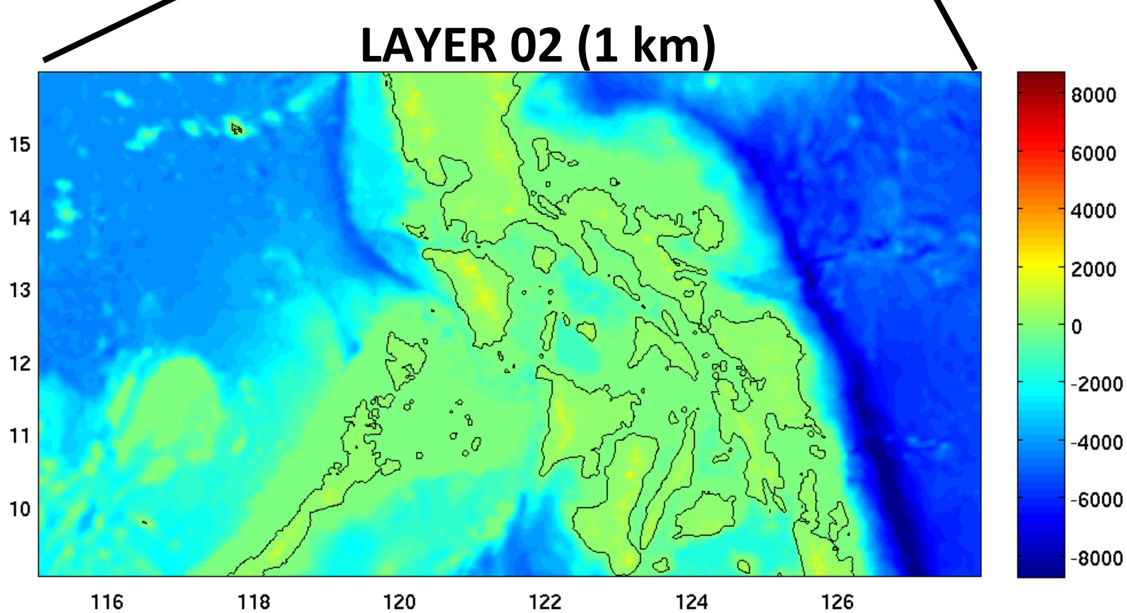
Barangay Rosal

1) Inundation height was measured at 5.9 m near the San Juanico Bridge.
2) Sea wall damage at Tagpuro and the run-up height was about 6.9 m.
3) Barangay Rosal area with a 5.0 m storm surge inundation and damage to houses behind the 3.0 m sea wall.

(Mas et al., 2015, Natural Hazards and Earth System SCI.)

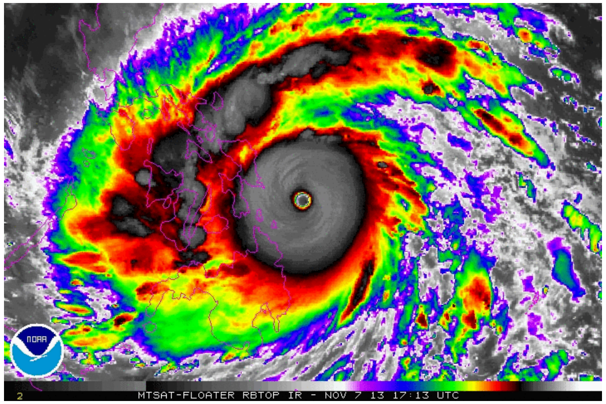
Nested Computational Domains in the Philippines



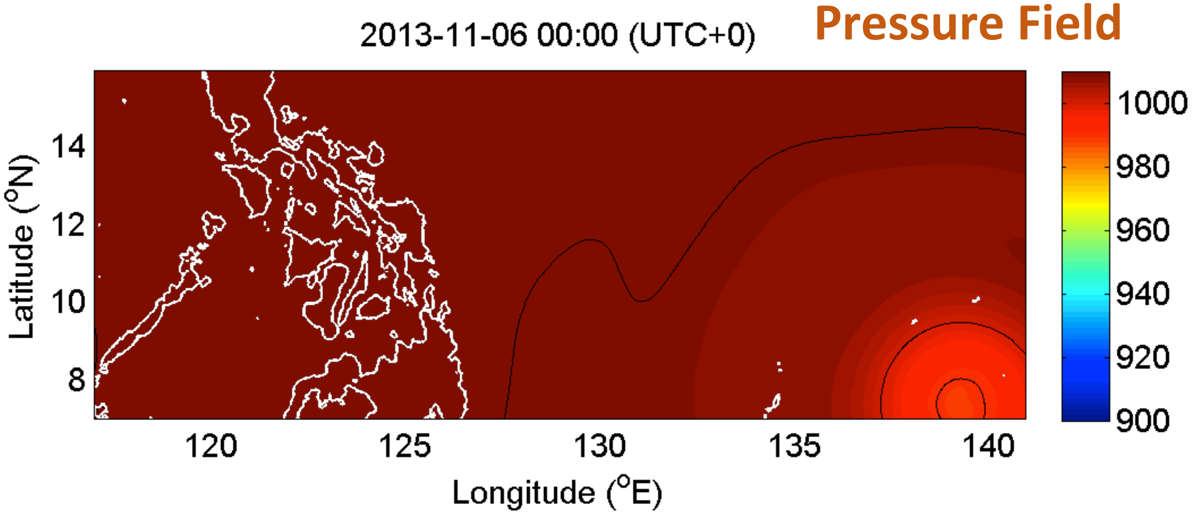


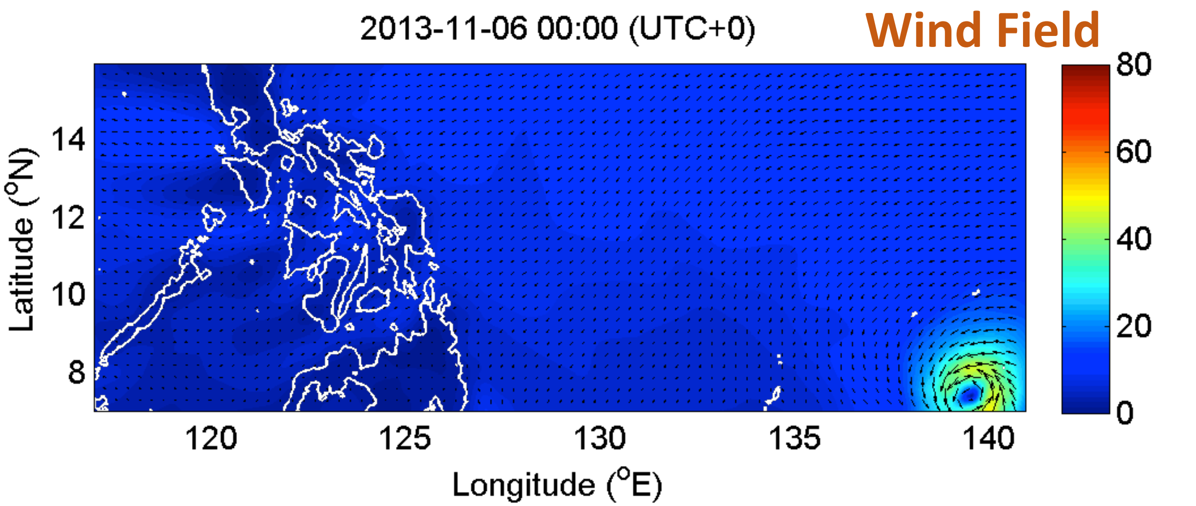
- Layer 01 can cover the complete typhoon life cycle of Typhoon Haiyan and the full storm surge propagation.
- Layer 02 can include the offshore hydrodynamic progresses of storm surge on the fine mesh domain.

Couple with the Atmospheric WRF Model



- *Asymmetric effect*
- *Topographic effect*
- *Hydrodynamic Pressure*

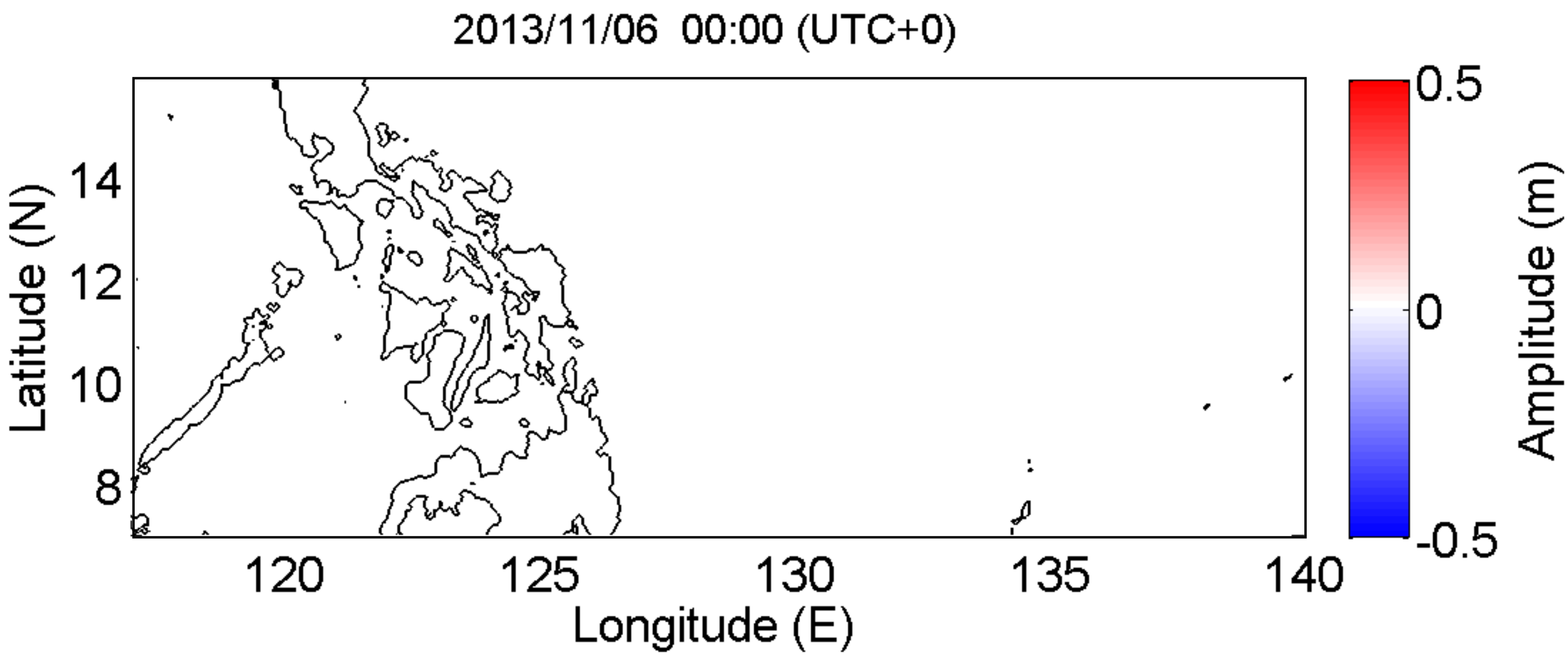




The WRF simulations are provided by Dr. Chuan-Yao Lin, AAR Modeling Laboratory (Sinica).

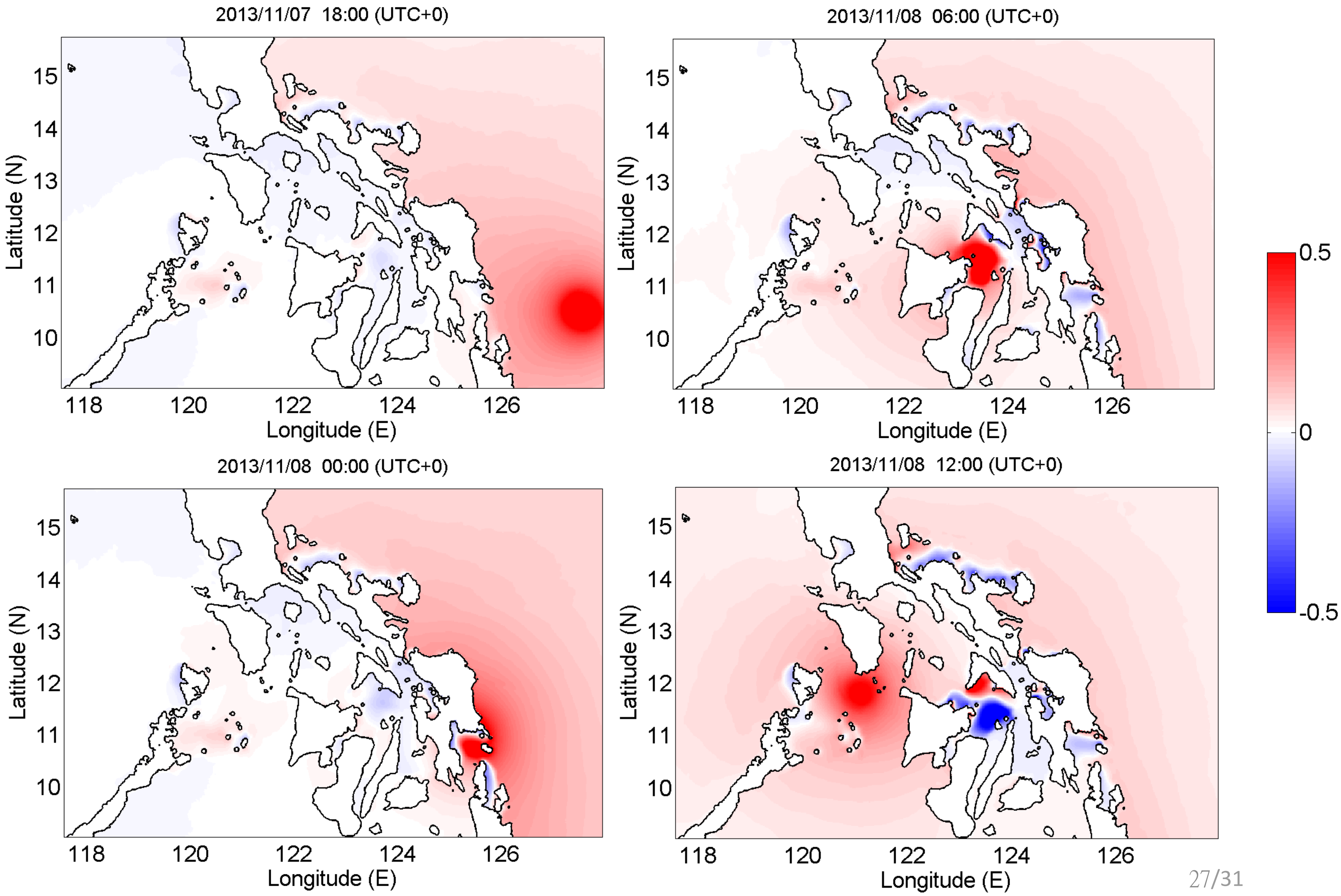
Storm Surges Induced by Typhoon Haiyan

2013.11.06 00:00 – 2013.11.09 00:00 (UTC+0)

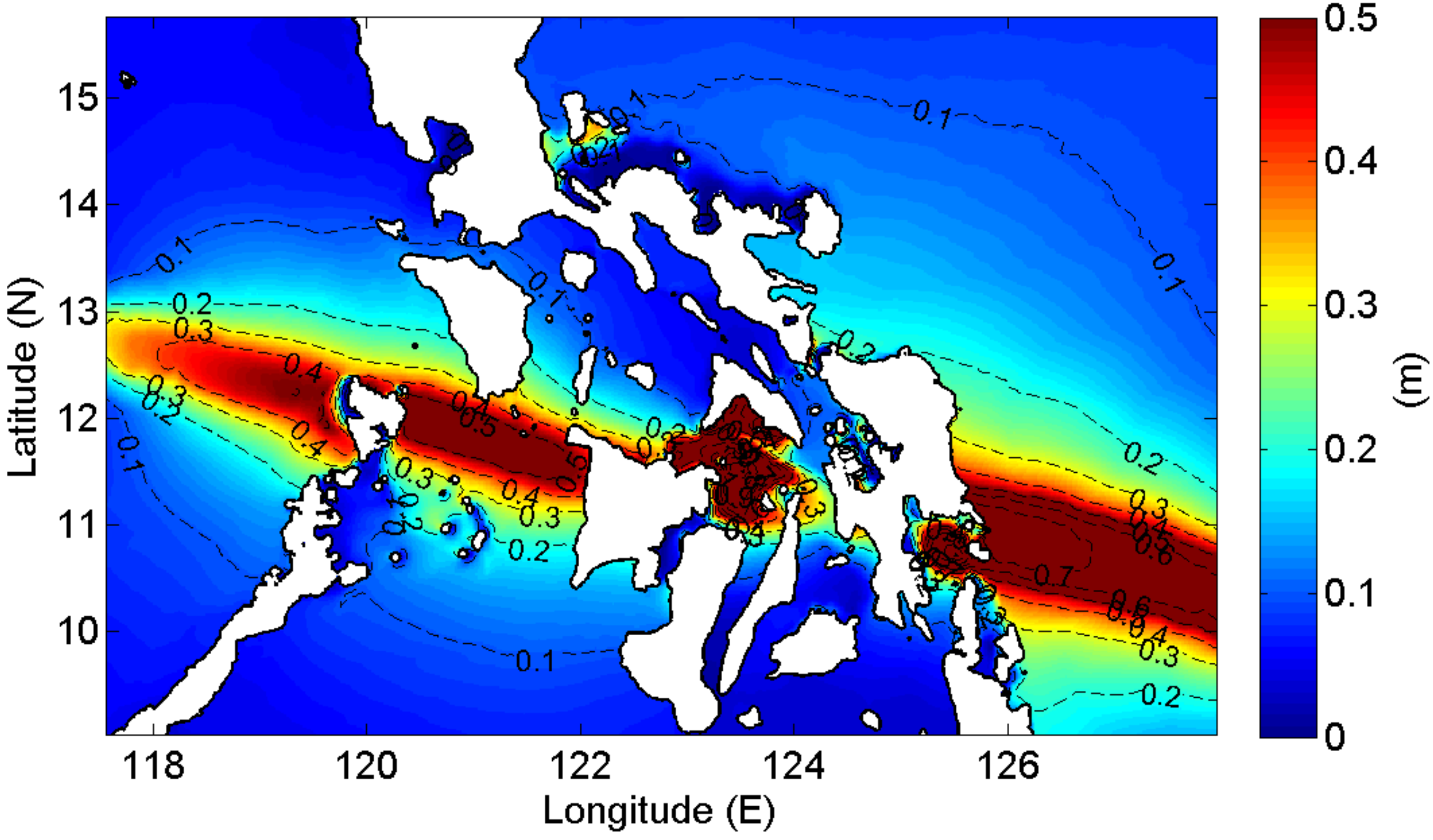


The full storm surge propagation induced by Typhoon Haiyan can be simulated by our storm surge model.

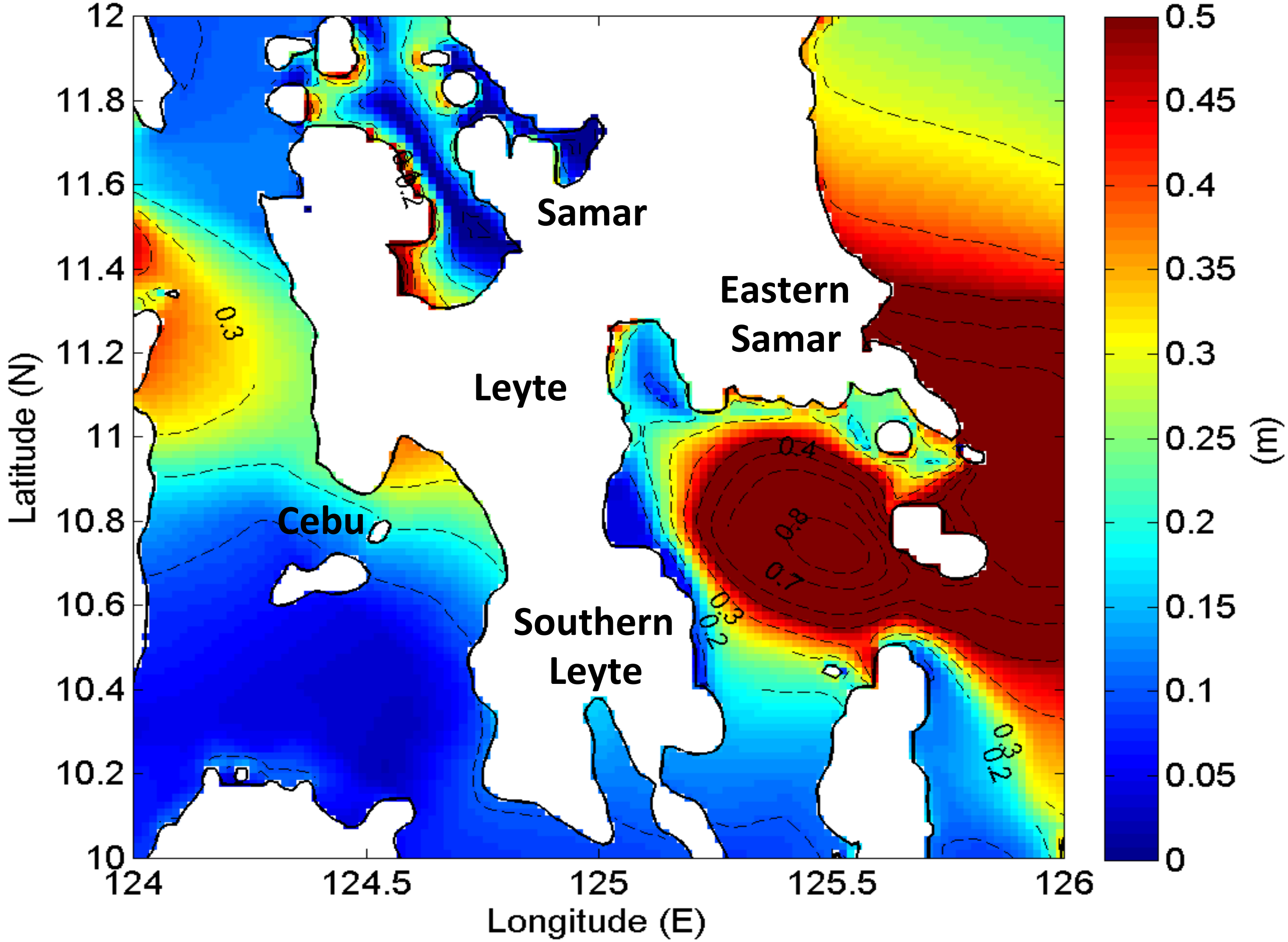
Snapshots of Storm Surges in the Philippines



The Maximum Storm Surges in the Philippines

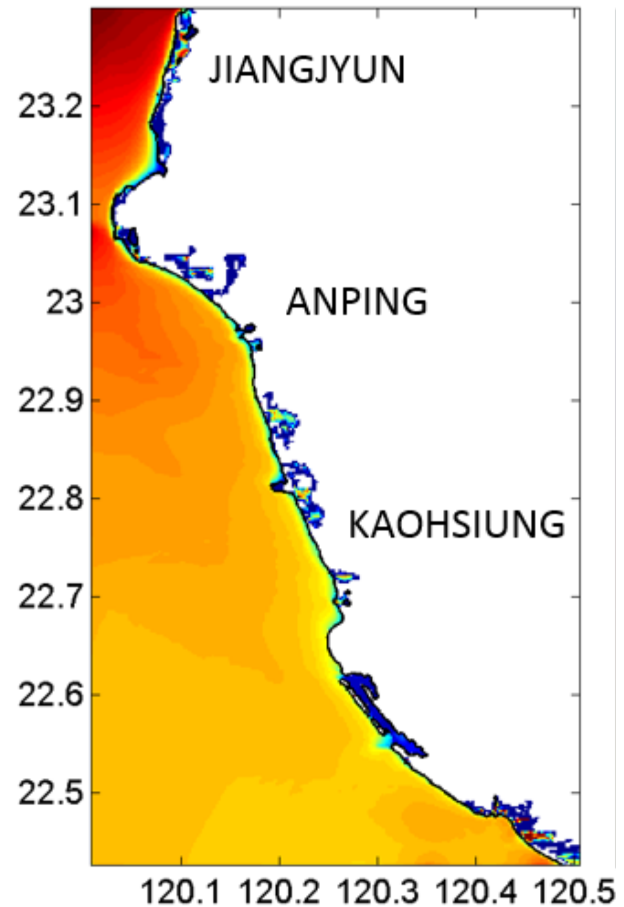


Offshore Storm Surge Inundation Induced by Typhoon Haiyan



Conclusion (1)

- Our storm surge model is better than ever, and have many advantages:
  - Adopt the **large computational domain** to cover the complete typhoon life cycle and full storm surge propagation.
  - Couple with the **dynamic atmospheric WRF model**.
  - Couple with the **global TPXO model**.
  - Calculate **high-resolution storm surge inundation**.
  - **High-speed calculation** for the operational system.



Conclusion (2)

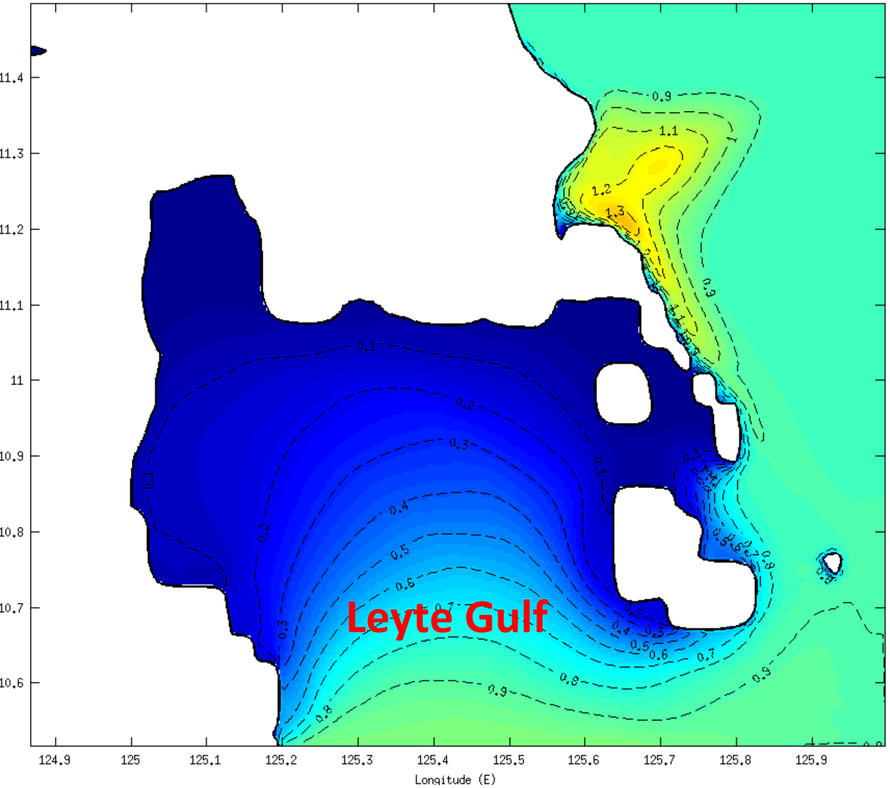
- What we will do for the next step on 2013 Typhoon Haiyan
  - Calculate **high-resolution storm surge inundation** in coastal regions
  - Compare with **offshore tidal gauge data**.
  - Validate with field-survey surge inundation.

- We are glad to cooperate with everyone:
  - Countries under the threat of storm surges
  - Organizations which require the hazard map for disaster mitigation
  - Research centers which need the storm surge modeling
  - And so on.

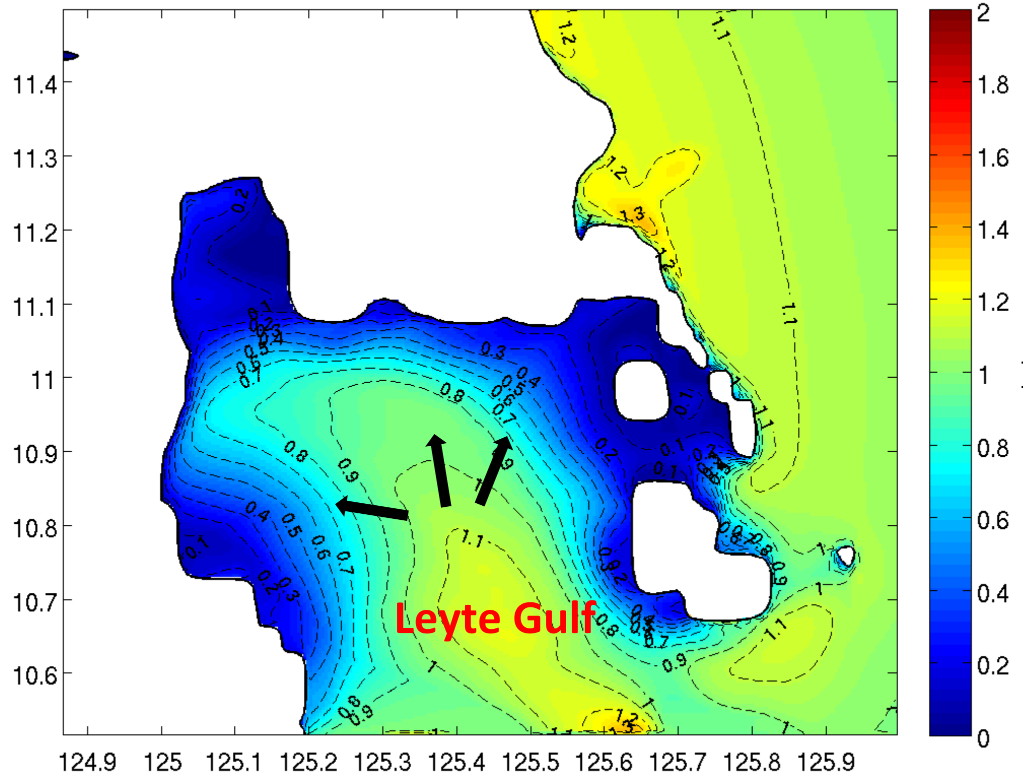
- Welcome comments and discussion. Thanks!

Test Case for Coupling with the Global Tidal Model

Pure Max Tidal Height

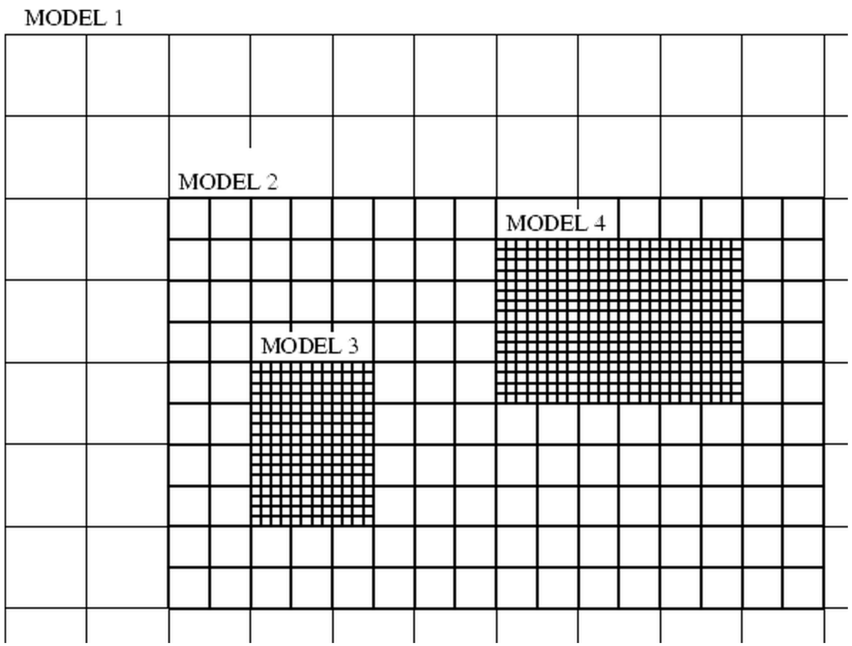


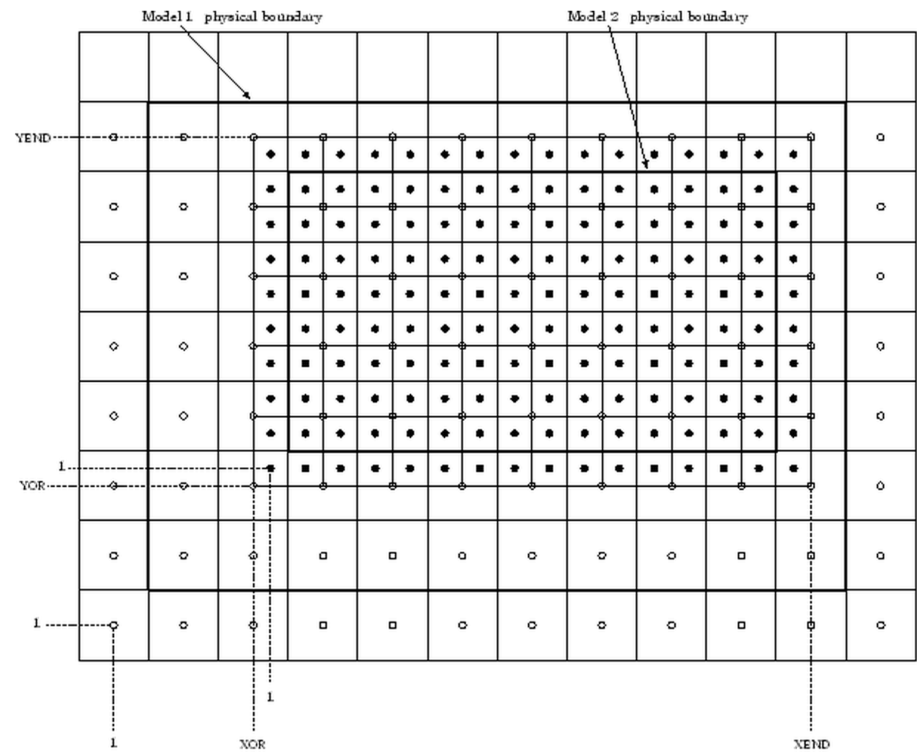
Max Storm Surge Height with Tidal Effect



Need more data to validate the simulated results.

Nested-Grid Scheme for Multi-scale Storm Surge Propagation





(T. L Clark, 1984; C. Chen, 1991; and Y. G. Kurihara, J. Tripoli and M. A. Bender, 1979)

- Communication between coarse grid resolution and fine grid resolution.
- Make fast calculation of fine-grid storm surge inundation possible.
- High efficiency and more stable than unstructured grid system.