Disaster Mitigation Workshop

APAN 43 at New Delhi, Indian

Development of Storm Surge Fast-Calculation Model and Case Study of 2013 Typhoon Haiyan

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

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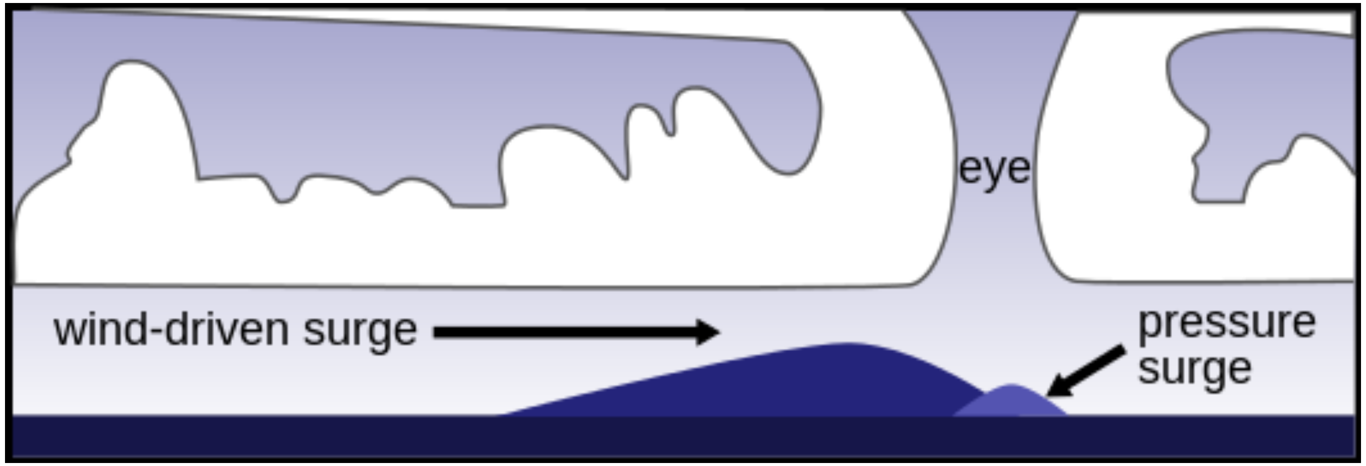
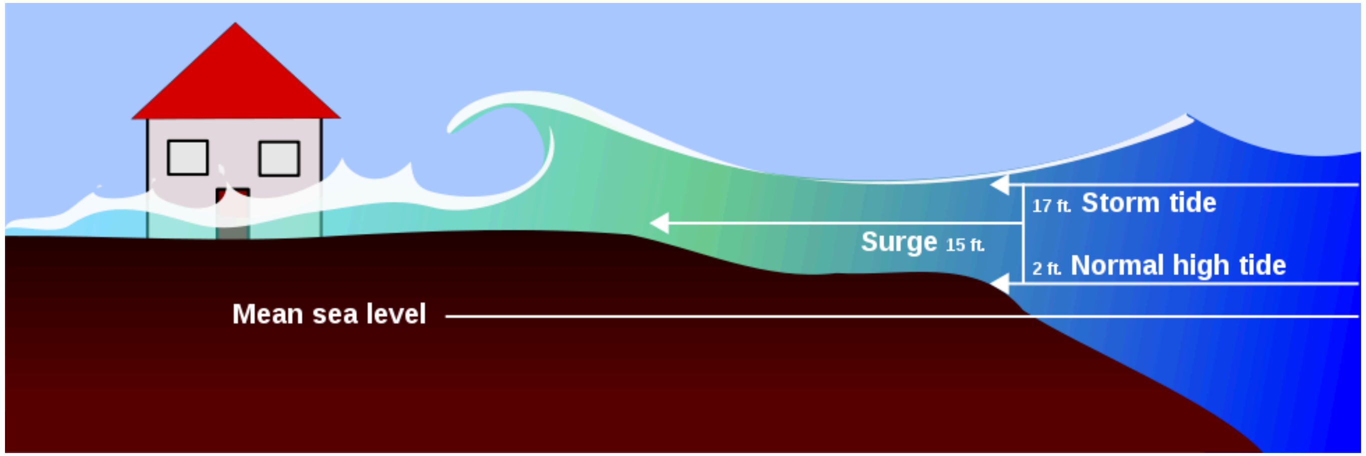
STORM SURGE



Sea Surface induced by typhoons (Wiki)



Tidal Effect with Storm Surges (Wiki)

- Storm surge is a coastal flood of rising water commonly associated with low pressure weather systems :
  - ✓ **Tropical cyclones**
  - ✓ **Storms**
  - ✓ **Typhoons**
  - ✓ **Hurricanes**

- The two main meteorological factors contributing to a storm surge are:
  - ✓ **Pressure gradient**
  - ✓ **Wind shear stress**

Inundation induced by Storm Surges

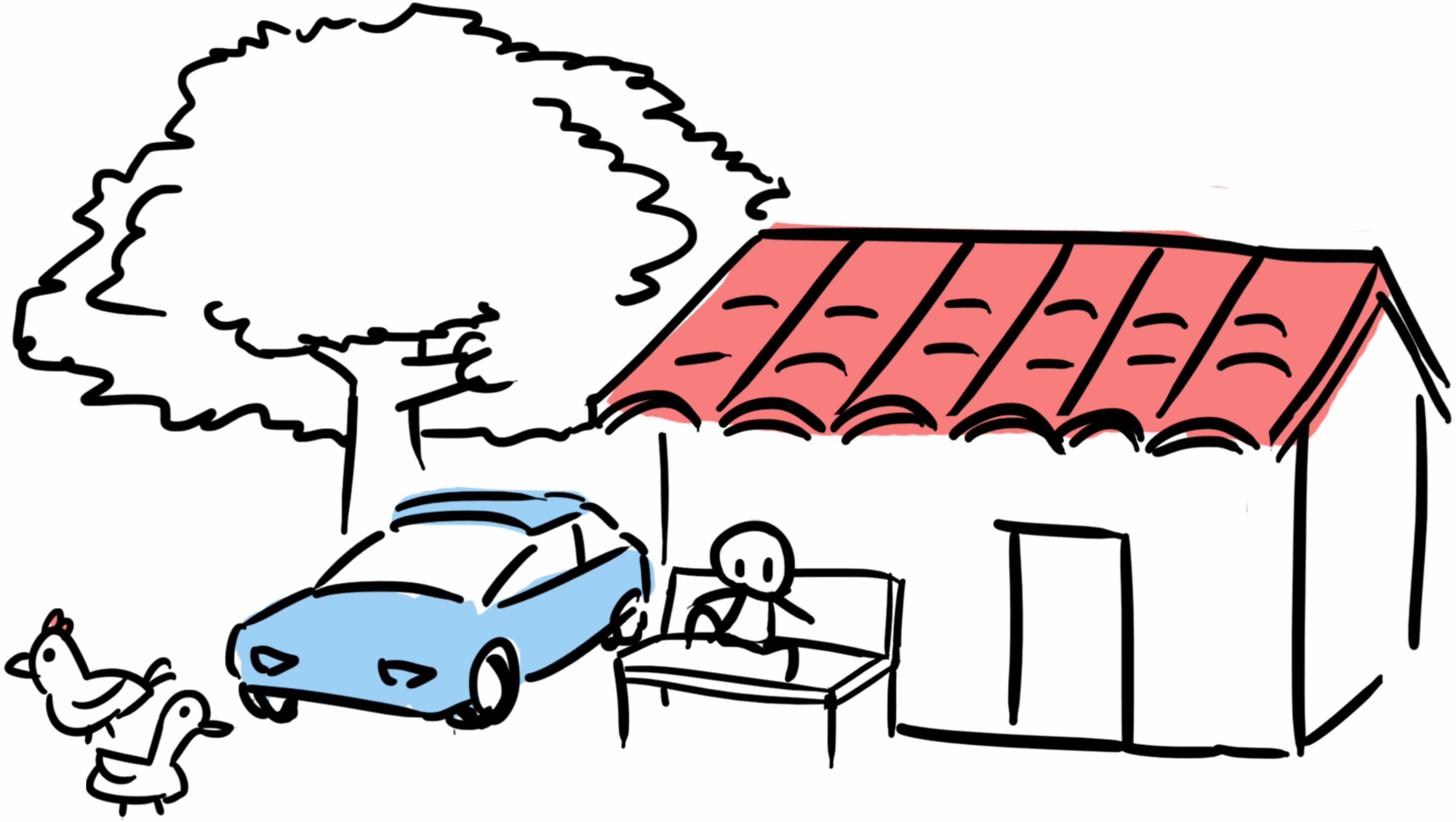
- *Destroy of homes and business*
- *Potential threat of coastal communities*
- *Damages of roads and bridges*

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

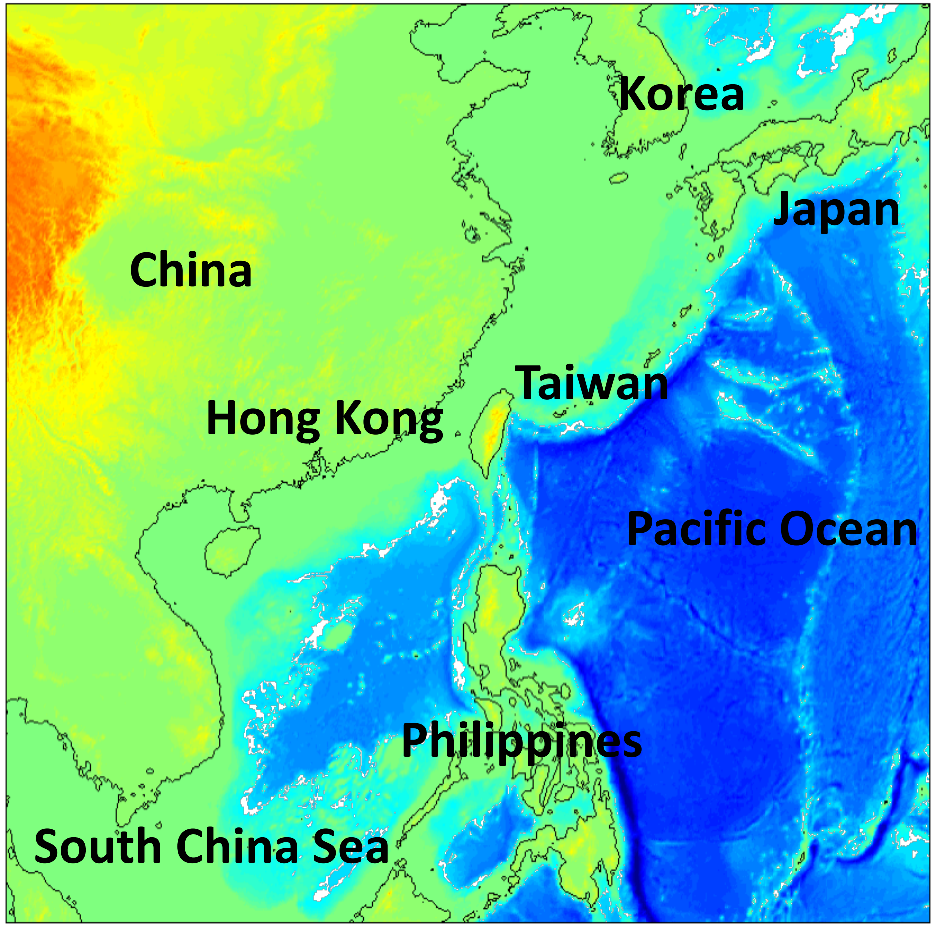
Inundation induced by 2005 Hurricane Katrina. (http://www.stormsurge.noaa.gov/)

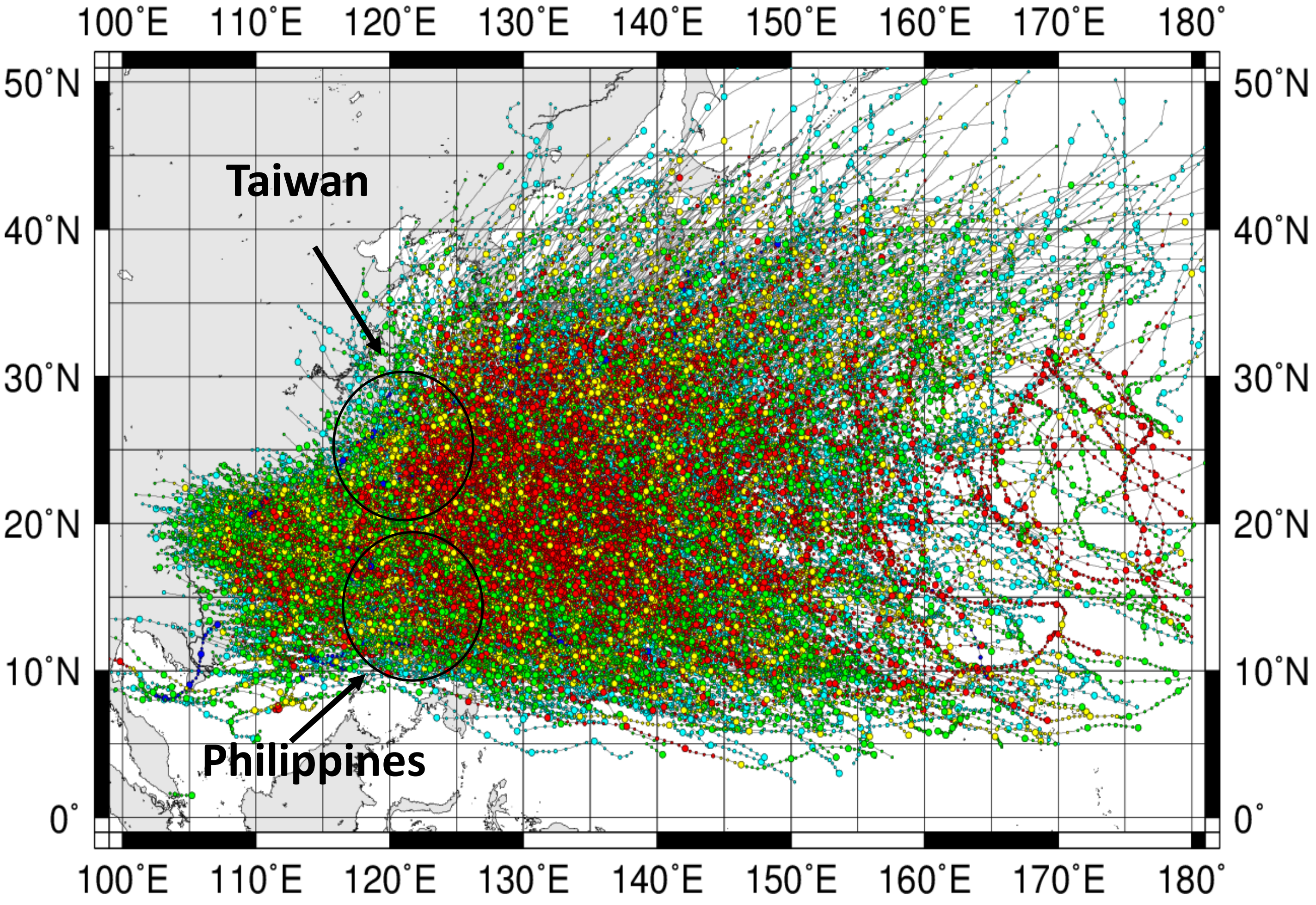
Flooded by storm surge of Hurricane Katrina (2005) in the northwest New Orleans.

Inundation induced by Storm Surges



Typhoons in East Asia

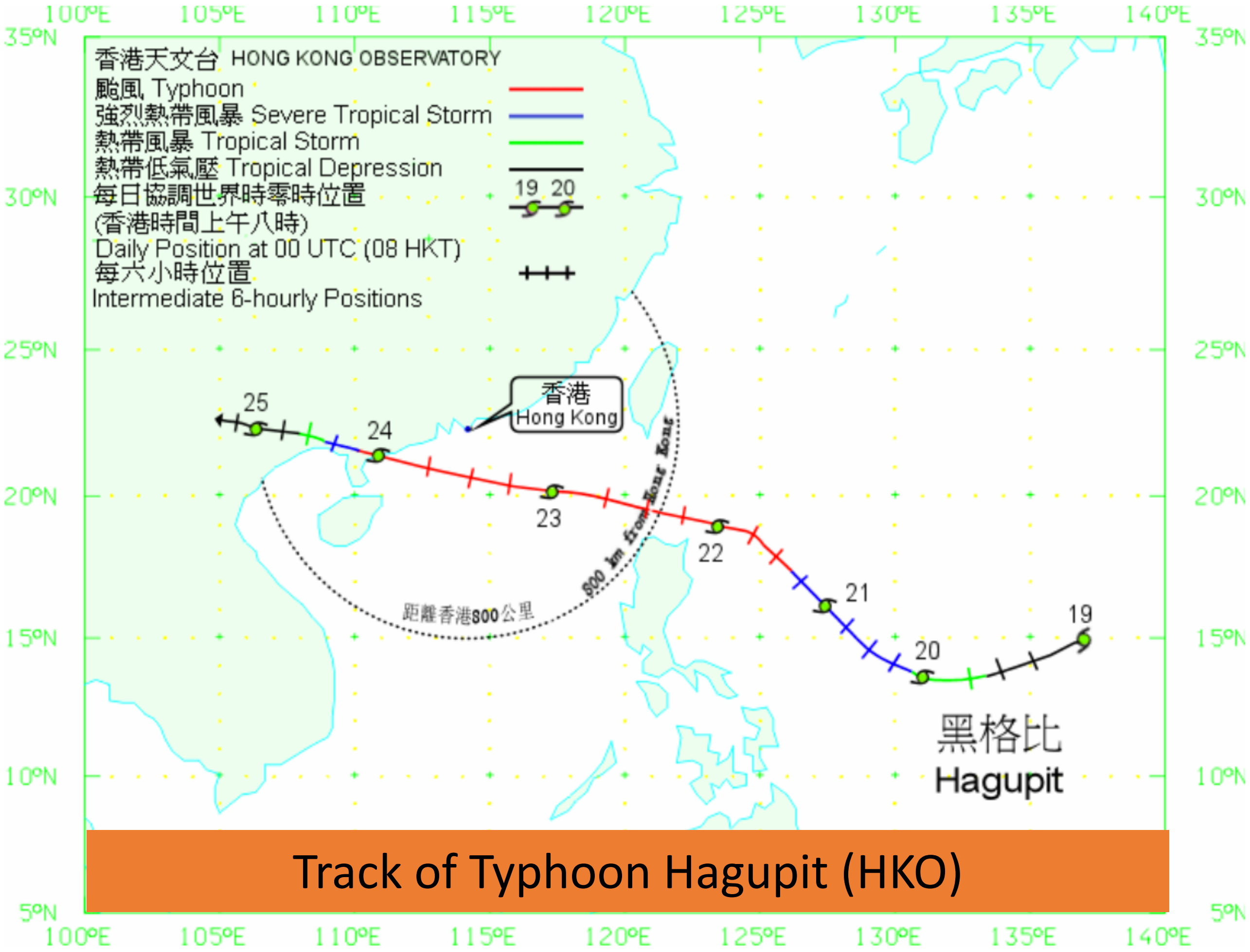




Tracks of all tropical cyclones in the northwestern Pacific Ocean between 1951 and 2014.

Hong Kong - Catogory-4 Typhoon Hagupit

2008.09.19 – 2008.09.25

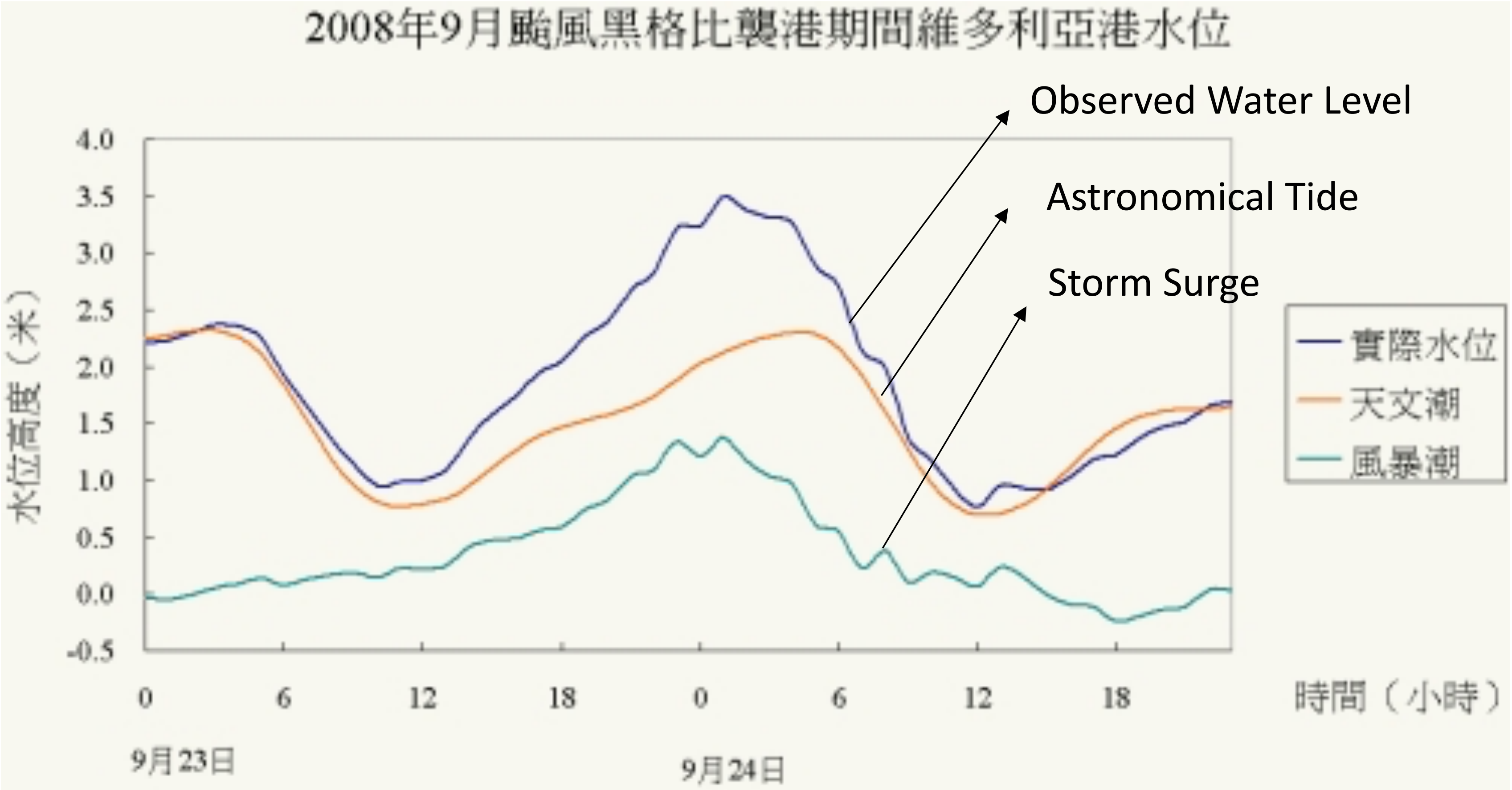


Track of Typhoon Hagupit (HKO)

Hong Kong Local News

Saltwater Intrusion

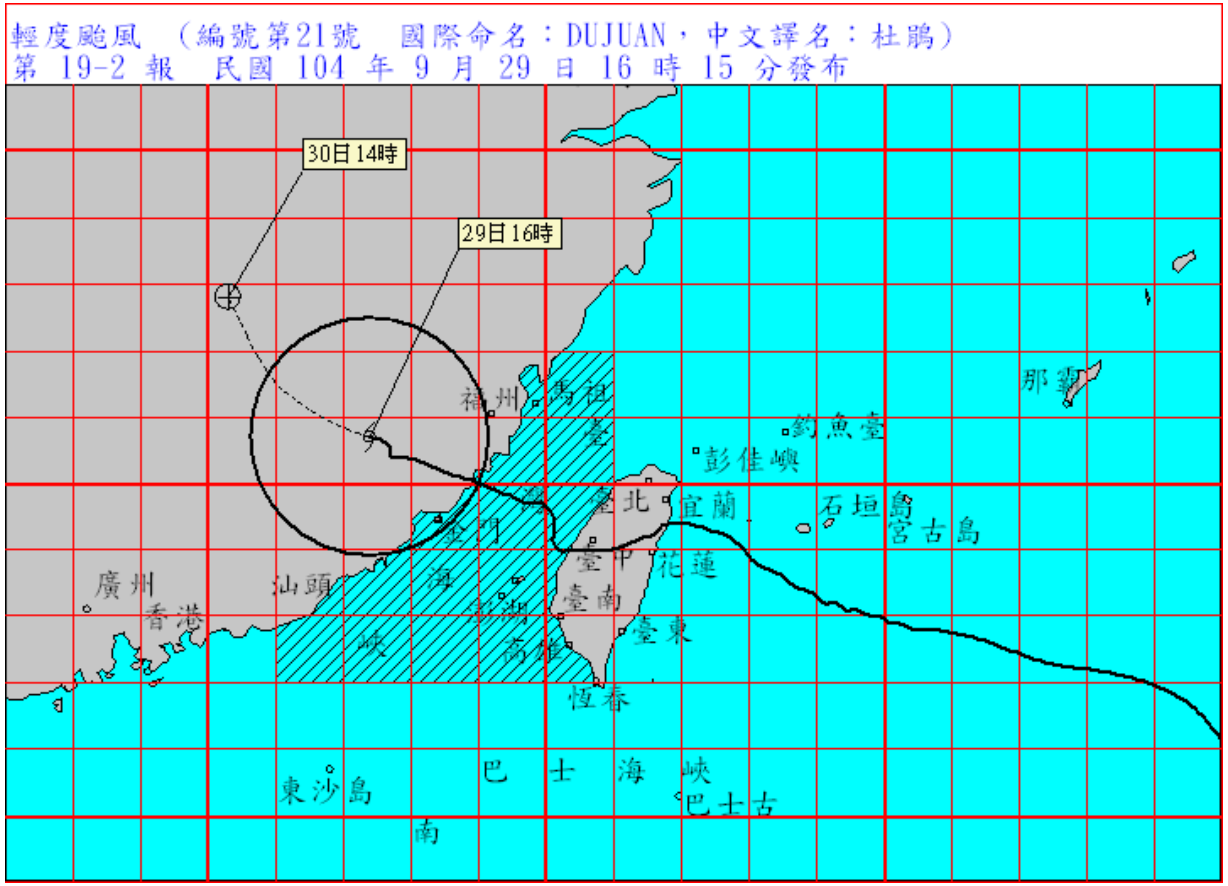
Records of Storm Surge at Victoria Harbour



香港天文台 (Hong Kong Observatory)
http://www.weather.gov.hk/m/article_uc.htm?title=ele_00184

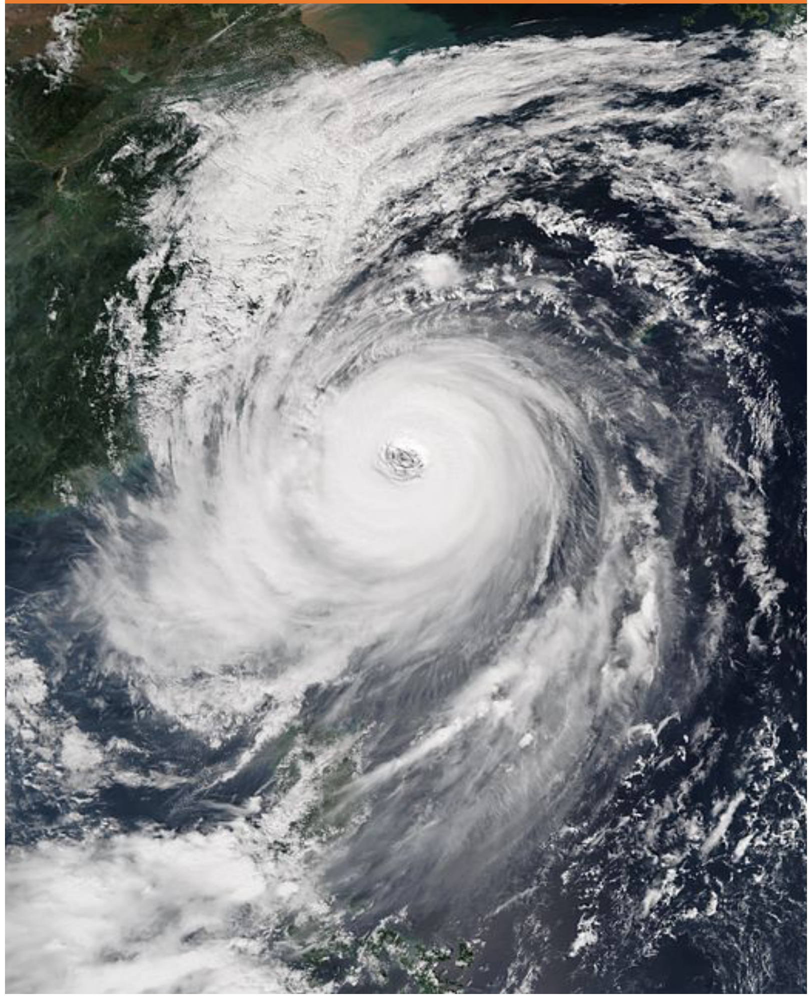
Taiwan – Catogory-4 Typhoon Dujuan

2015.09.15 – 2015.09.29



The lowest pressure of Typhoon Dujuan is 925 mb.
The highest 1—minute wind is 205 km/hr.

Satellite Image



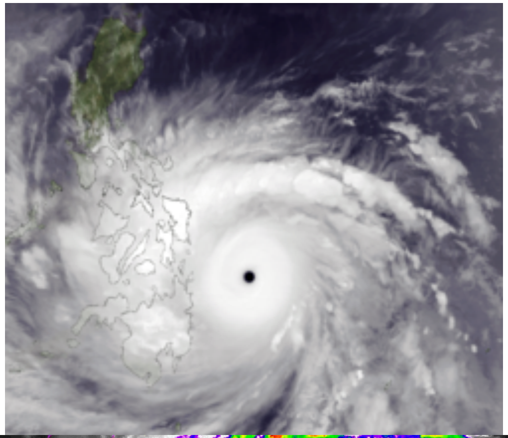
Inundation and Saltwater Intrusion

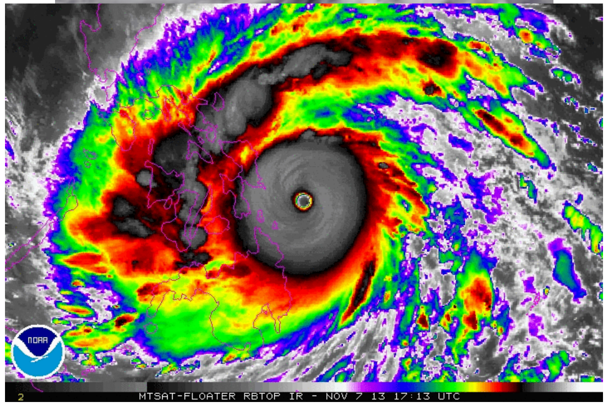
http://udn.com/news/story/3/1217285#prettyPhoto

2013 Super Typhoon Haiyan in the Philippines

Typhoon Life Cycle: November 3rd –November 11th

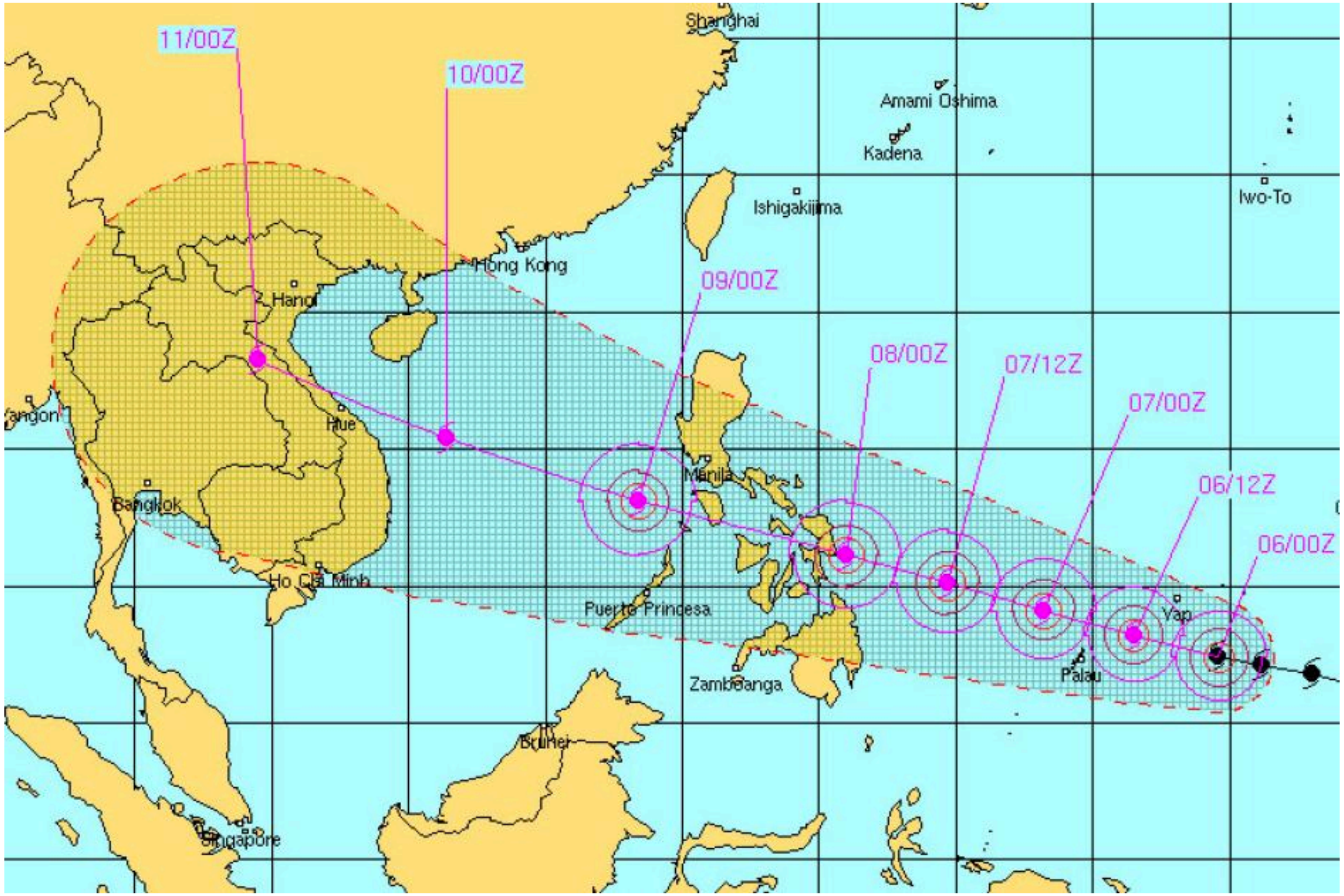
*Typhoon Haiyan: '**It was like the end of the world**'.*





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)

Field Survey after Typhoon Haiyan

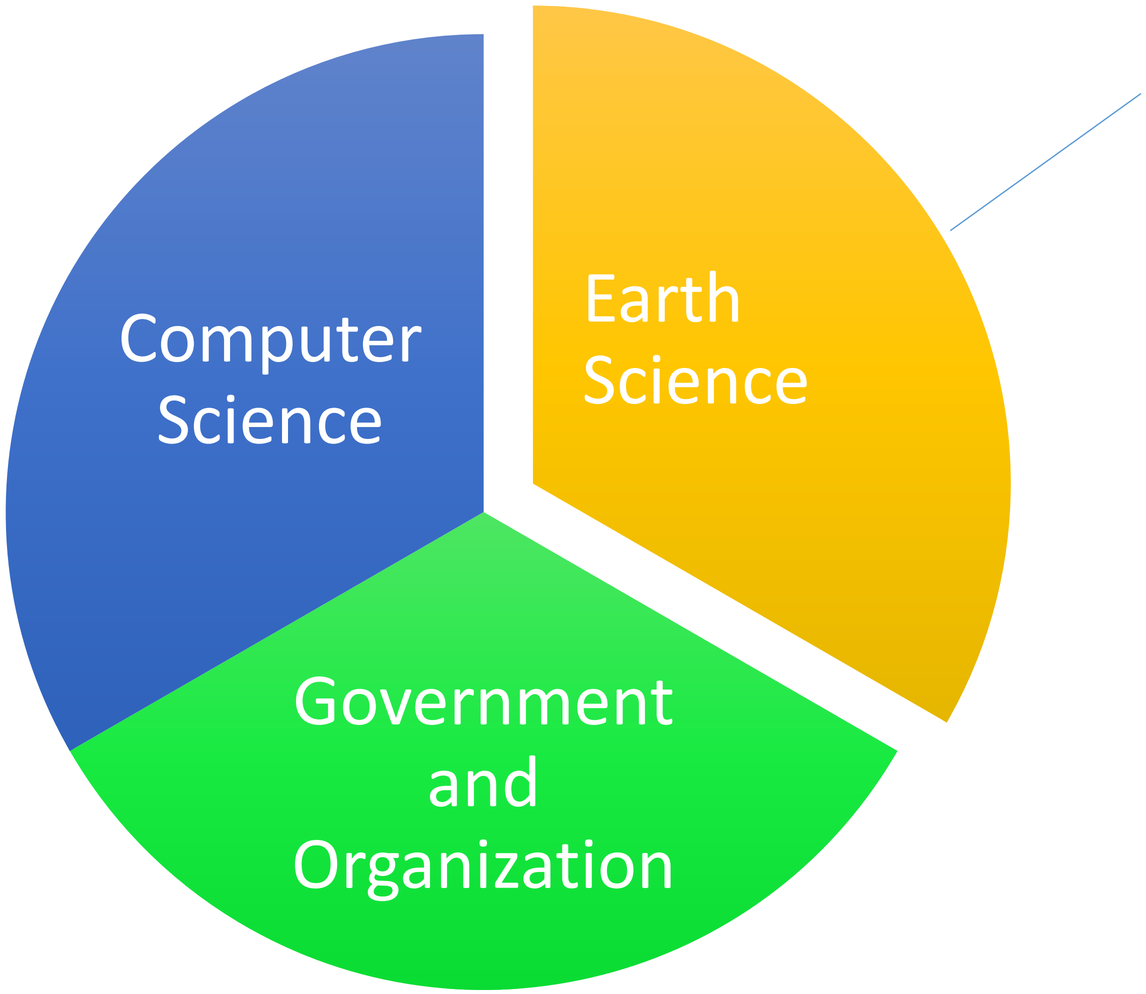
1) Inundation height was measured at **5.9 m** near the San Juanico Bridge.

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.)

Disaster Mitigation of Storm Surge Issue

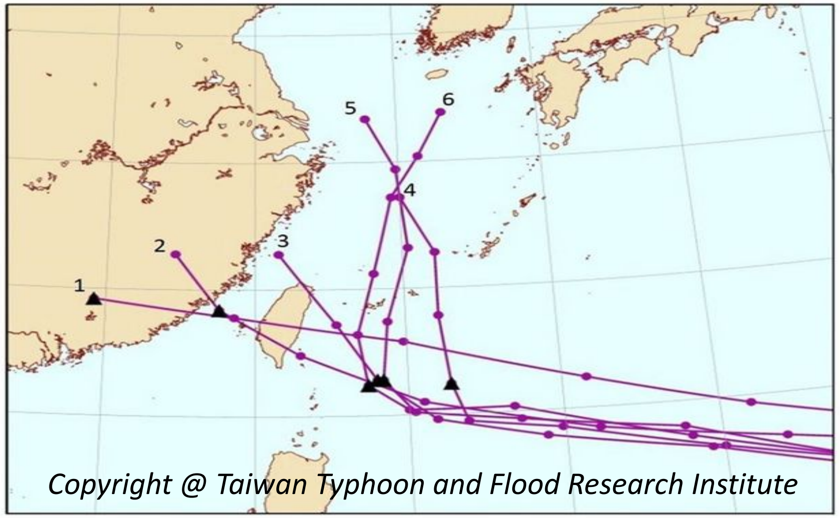


- **Aerodynamic Science**
  - Typhoon Pressure Field
  - Non-symmetric Wind field
  - Rainfall
  - Heat Transformation
  - And other physical factors

- **Hydrodynamic Science**
  - Storm Surge Propagation
  - Inundation Calculation
  - Tide-Surge Interaction
  - And other physical factors

Our Goals for a Storm Surge Operational System

- 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.
- High-resolution inundation calculation.
- Combine with the dynamic atmospheric model.
- Combine with the global tidal model.
- High-speed efficiency for the early-warning system.



Uncertainty of Storm Tracks

Multi-Scale Storm Surge Propagation (NOAA)

The Introduction of Storm Surge Model
(**CO**rnell **M**ulti-grid **CO**upled of **T**sunami 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.

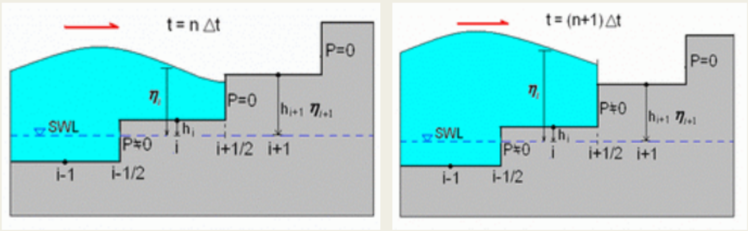


Fig.02 Moving Boundary Scheme

(1). Validation of Inundation Calculation

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

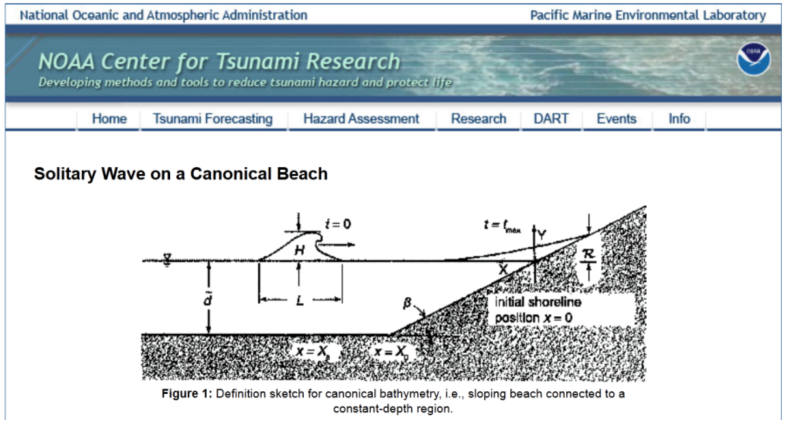
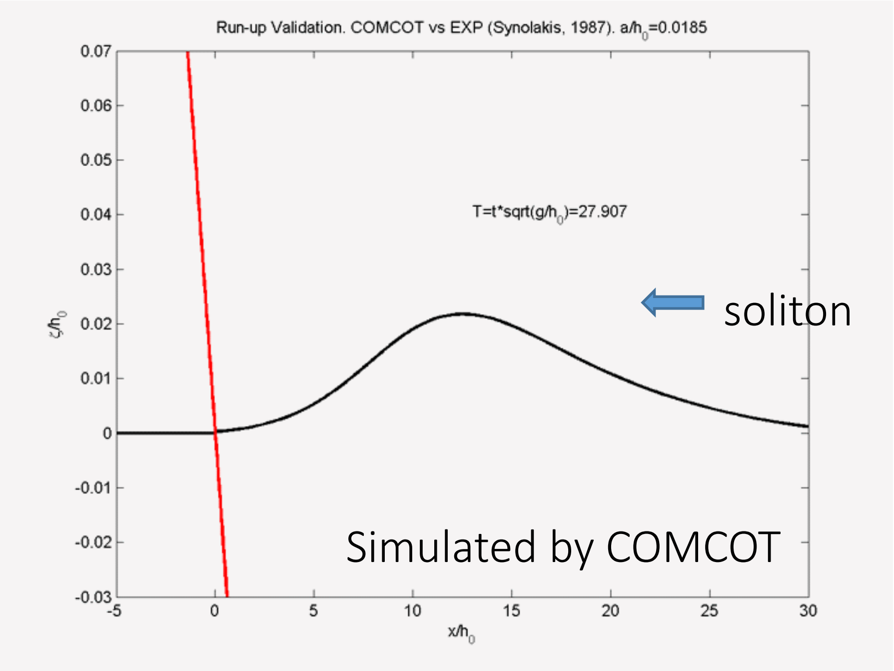
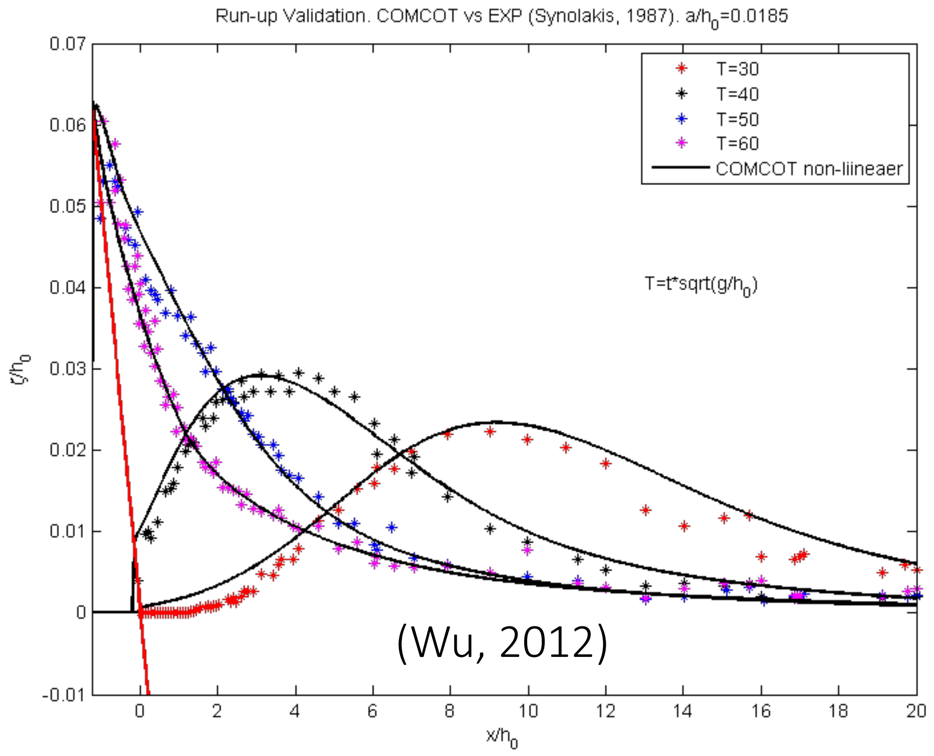


Figure 2: Time evolution of H = 0.0185 initial wave over a sloping beach with $\cot\beta = 19.85$ from $t = 25$ to 65 with 10 increments. Constant depth-segment starts at $X_0 = 19.85$. While markers show experimental results of Synolakis (1986, 1987), solid lines show nonlinear analytical solution of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

(from NOAA Official Website)



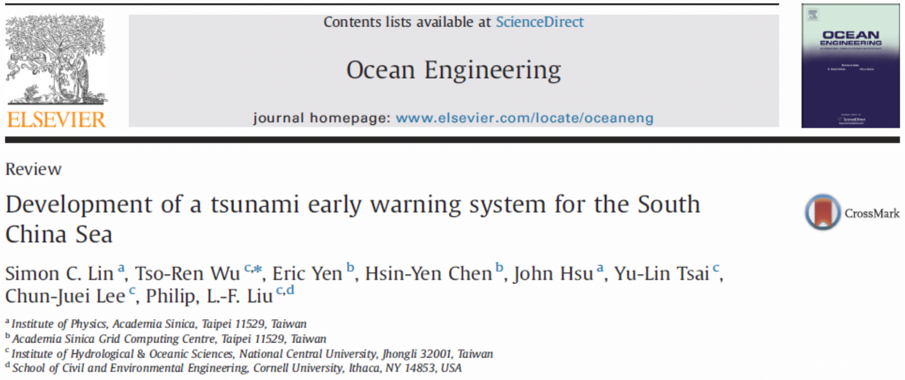


(2). High-speed Calculation

Our model can finish 48 hrs forecast in 1 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.



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]

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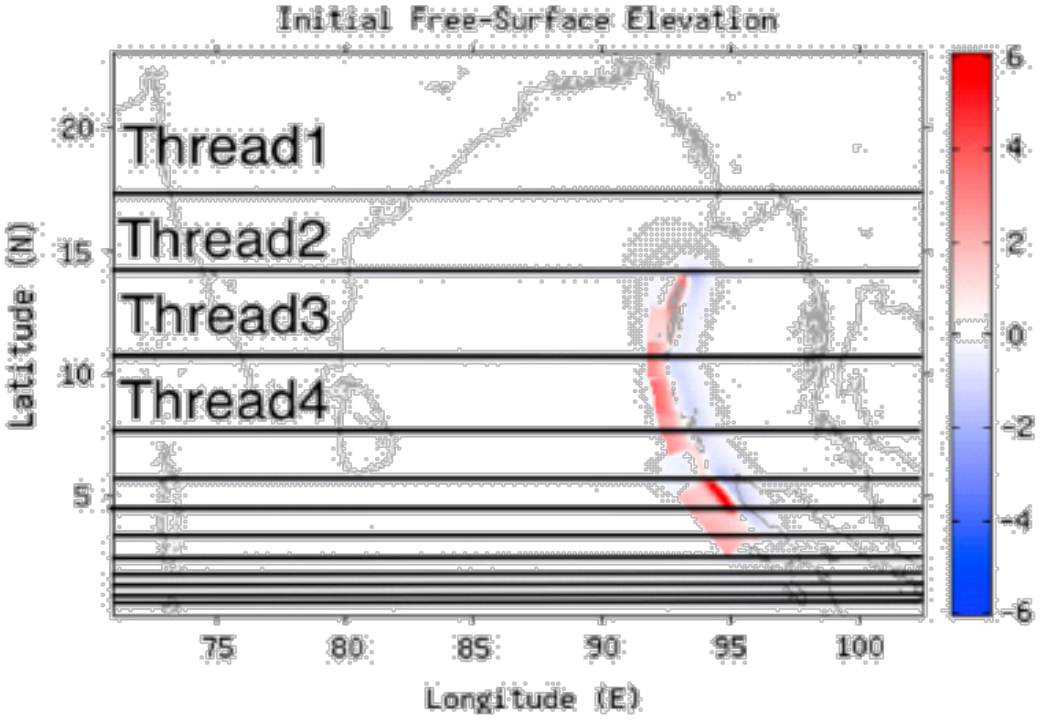
[b] Academia Sinica Grid Computing Centre, Taipei 11529, Taiwan
[c] Institute of Hydrological & Oceanic Sciences, National Central University, Jhongli 32001, Taiwan
[d] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

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

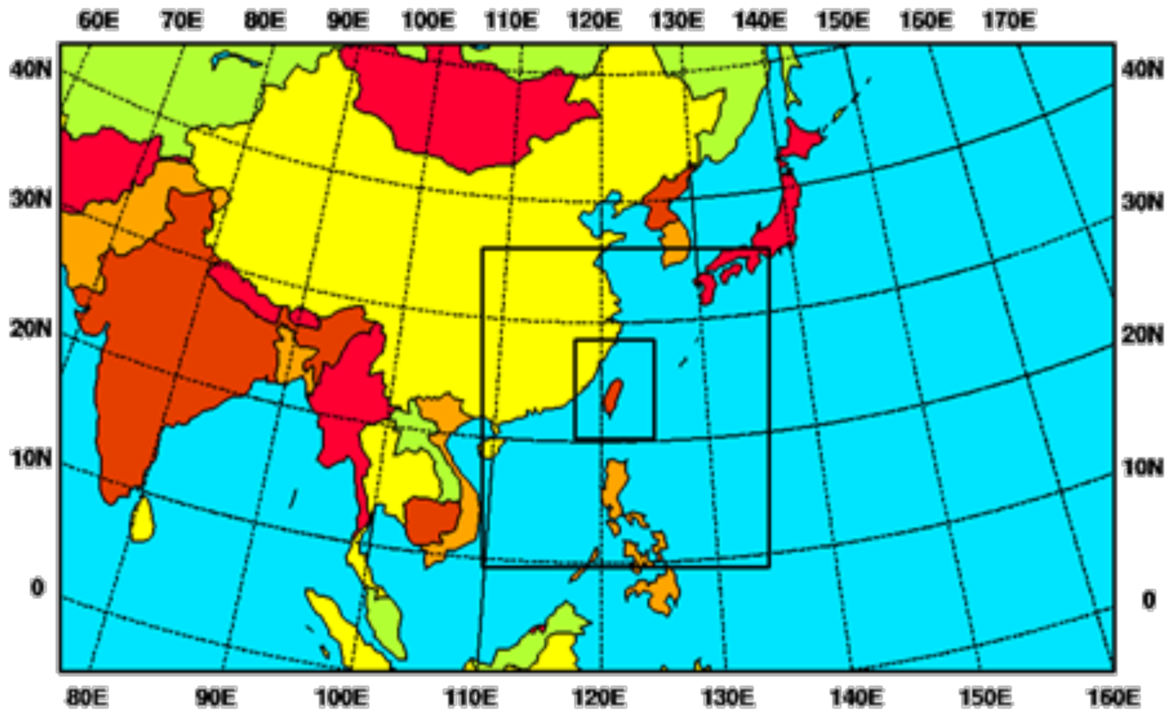


Dynamic resources sharing.

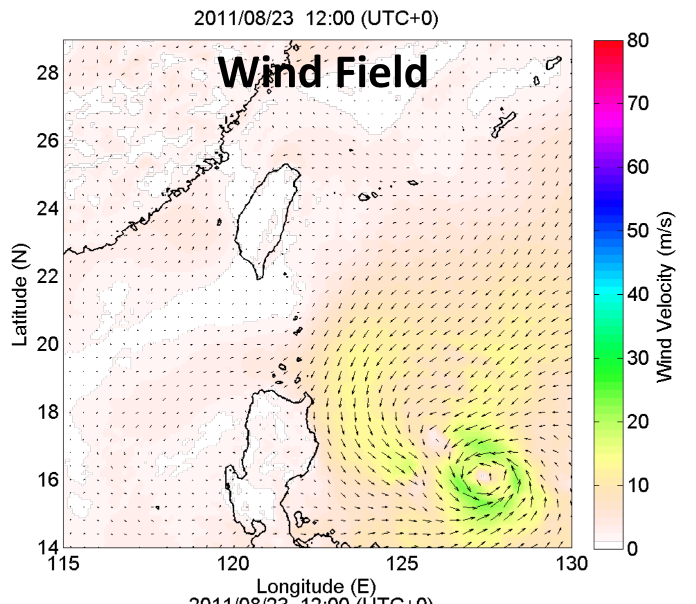
(3). Combine with the Atmospheric Model

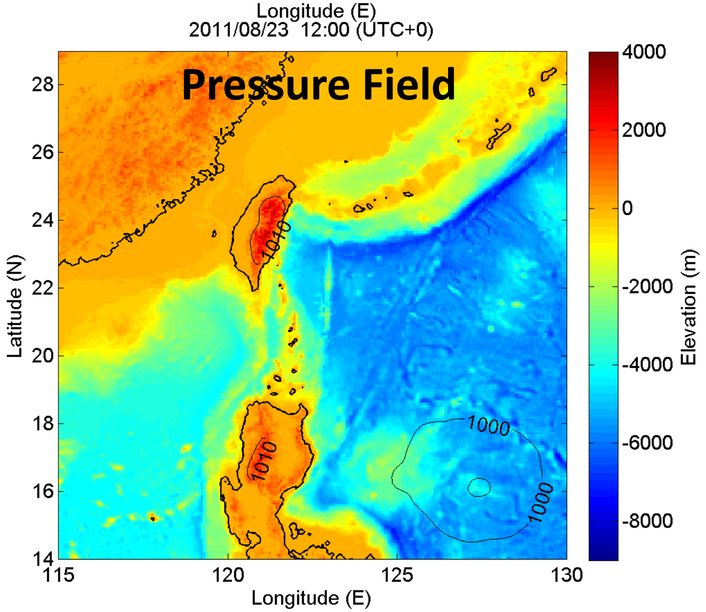
WRF (Weather Research and Forecasting Model)

- 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.



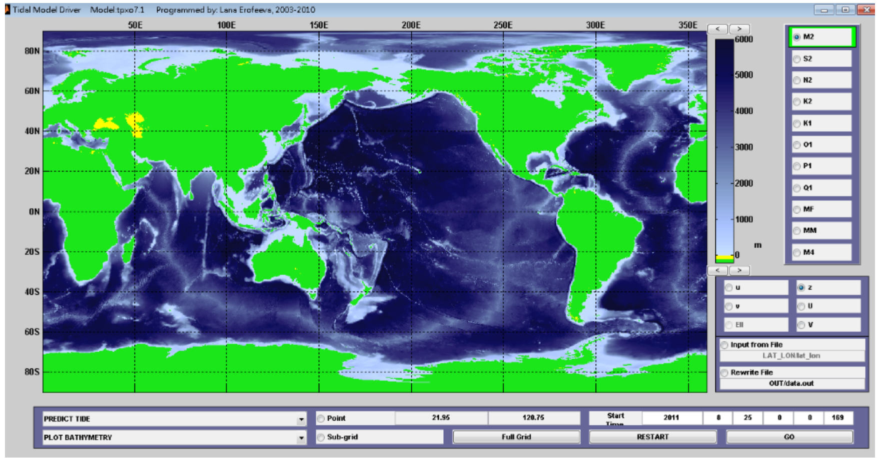
Computational Domain (CWB)



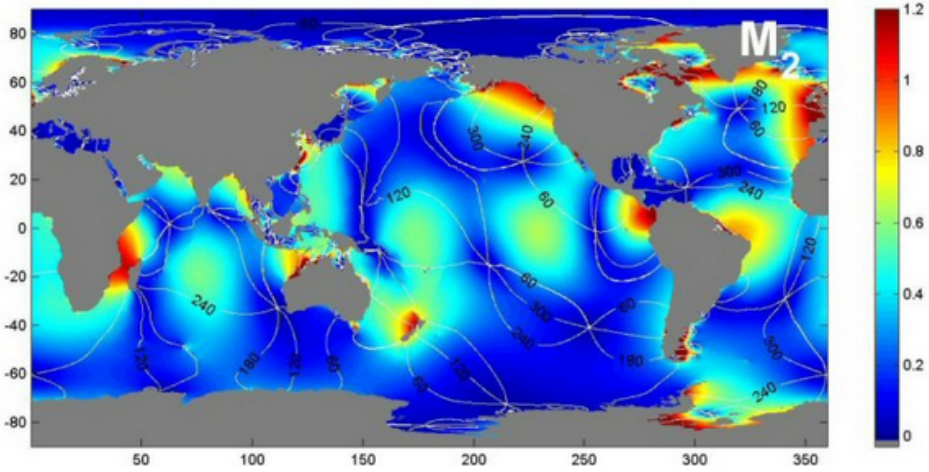


(4). Combine with Global Tide TPXO Model

(TOPEX/POSEIDON Global Tidal Model)



User Interface of TPXO



TPXO can provide tidal information, like M2.

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.

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]

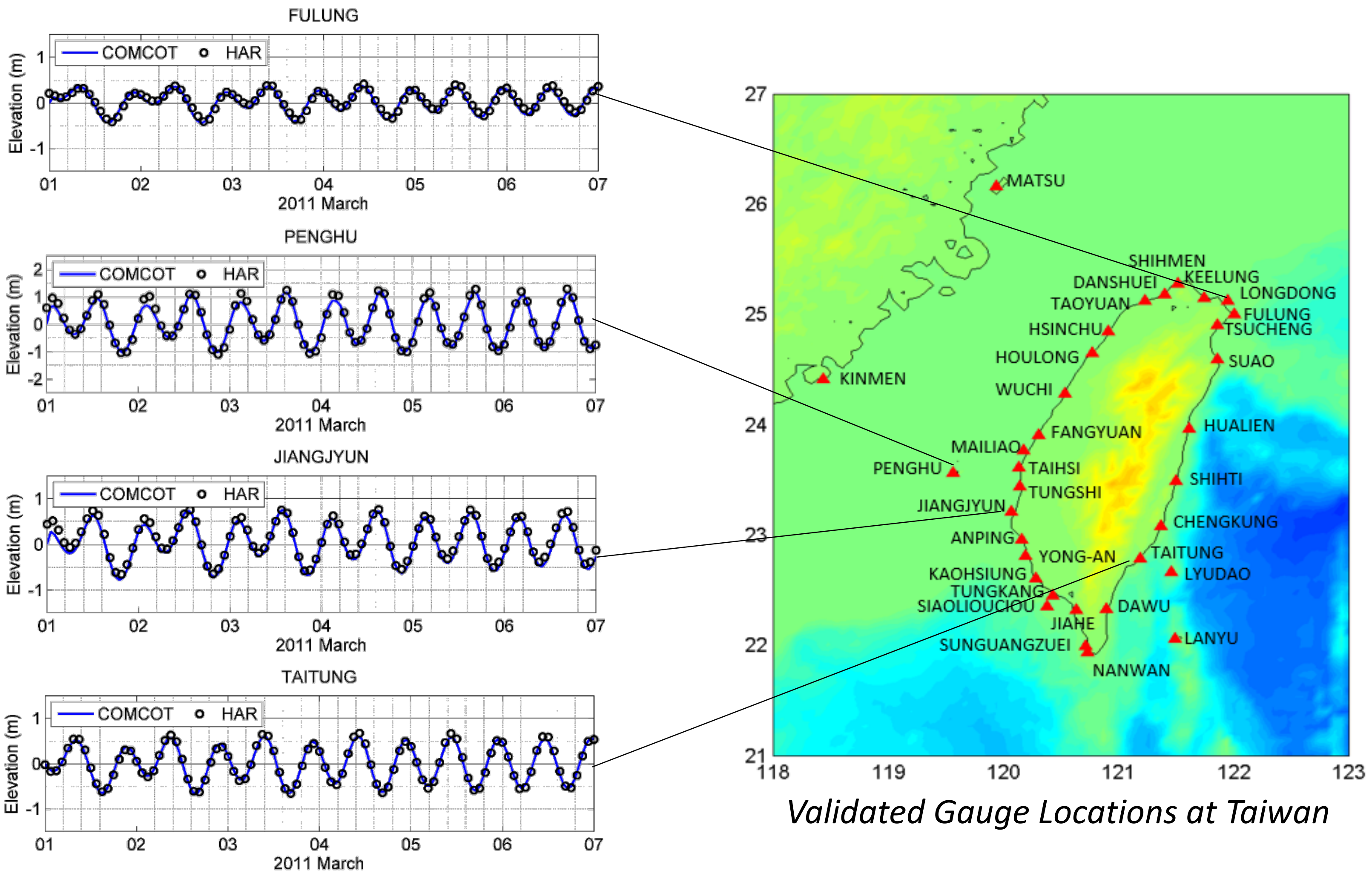
[1]*Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, Seattle, WA, U.S.A.*
[2]*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, U.S.A.*
[3]*Scripps Institution of Oceanography, La Jolla, CA, U.S.A.*
[4]*Department of Electrical 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 ($3\text{–}8 \times 10^{-9}$ s^{-1}, 210–310°) agree with those derived from the TPXO.2 model ($2\text{–}5 \times 10^{-9}$ s^{-1}, 250–300°), whereas harmonic constants of about ($1\text{–}2 \times 10^{-9}$ 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)

(5). High-Accuracy Tide Validation

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



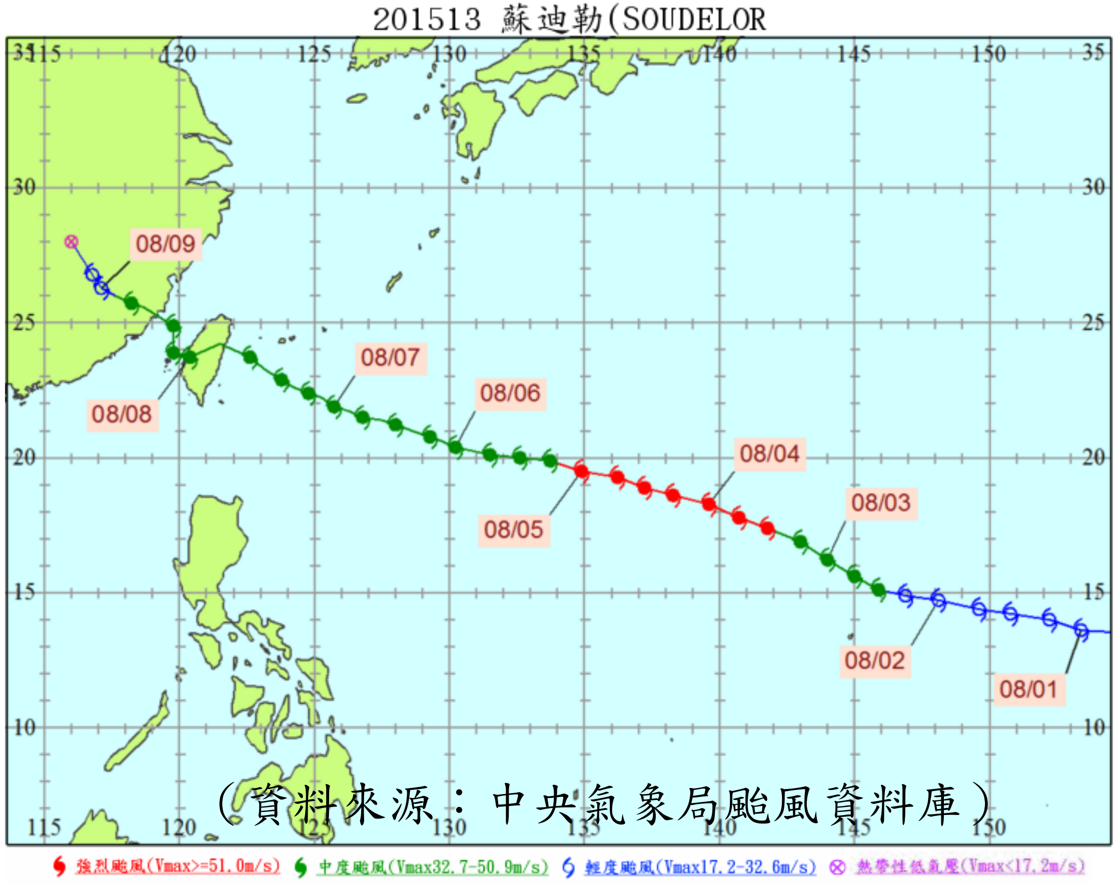
Validated Gauge Locations at Taiwan

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

Case Study of 2015 Typhoon Soudelor

- Typhoon Soudelor was the strongest typhoon in Western North Pacific regions at 2015. According to the brief analysis, more than 4,000 thousands families lost their electricity during typhoon period and accumulative rainfall is more than 1,000 mm.
- Because of the destructive damages, economic loss and human casualties at Mariana Islands, Taiwan, and China, the name “Soudelor” was removed from the list of typhoon names and would not be used forever.

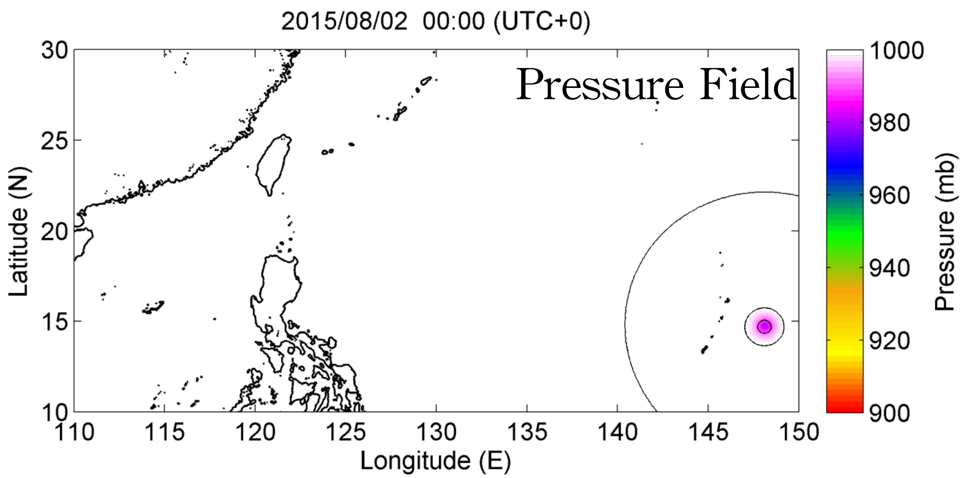
The flood in low-lying region at Ilan because of Typhoon Soudelor. (中央社記者沈如峰宜蘭縣)

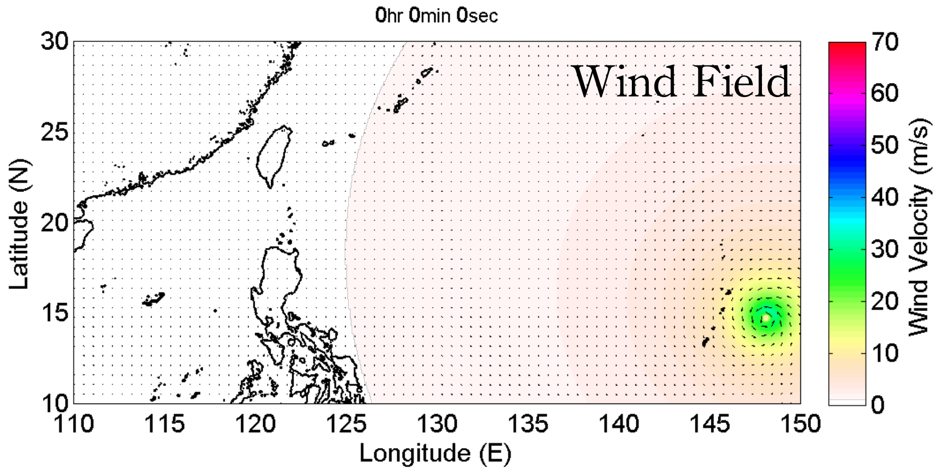


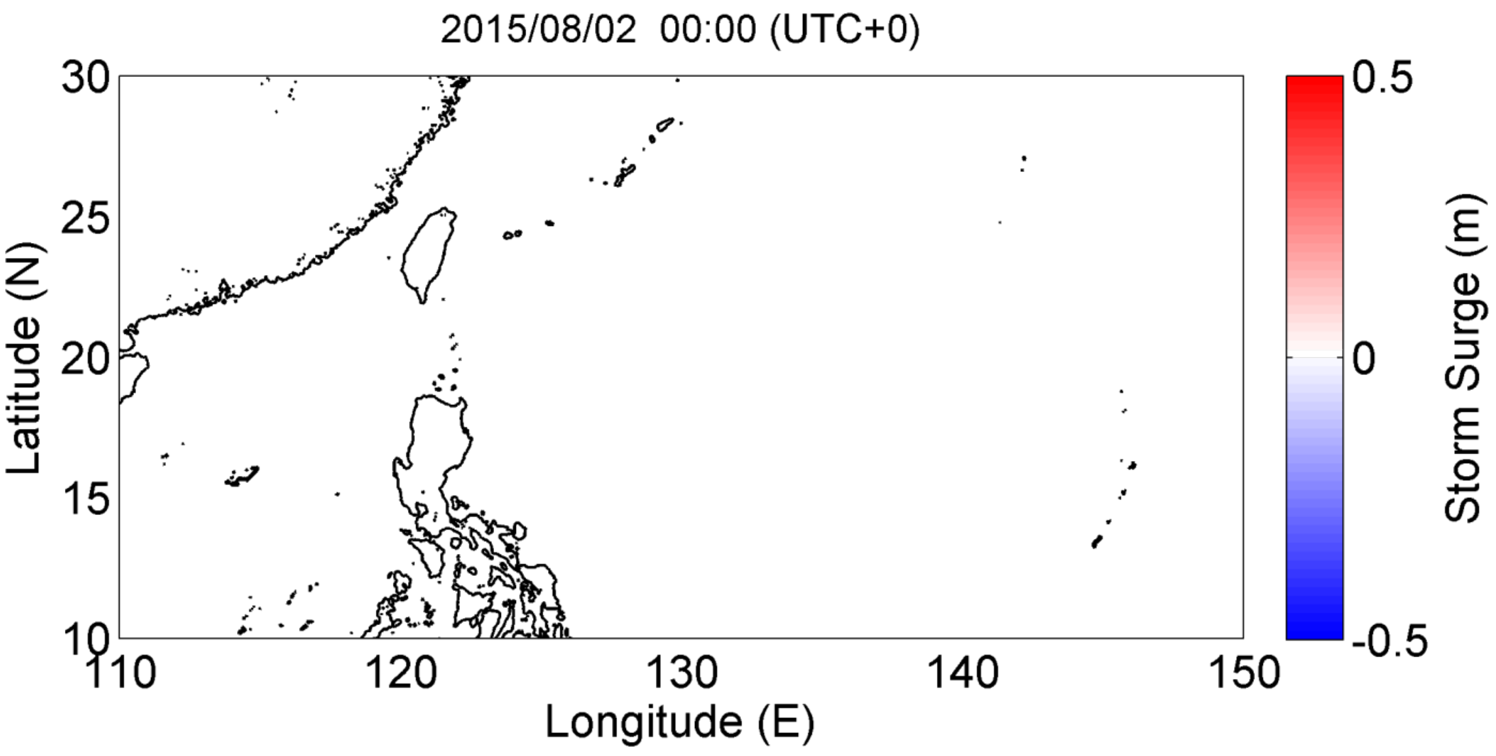
（資料來源：中央氣象局颱風資料庫）

Large-Scale Storm Surge Simulation on Spherical Coordinate System

2015.08.02 00:00 – 2015.08.09 06:00 (UTC)



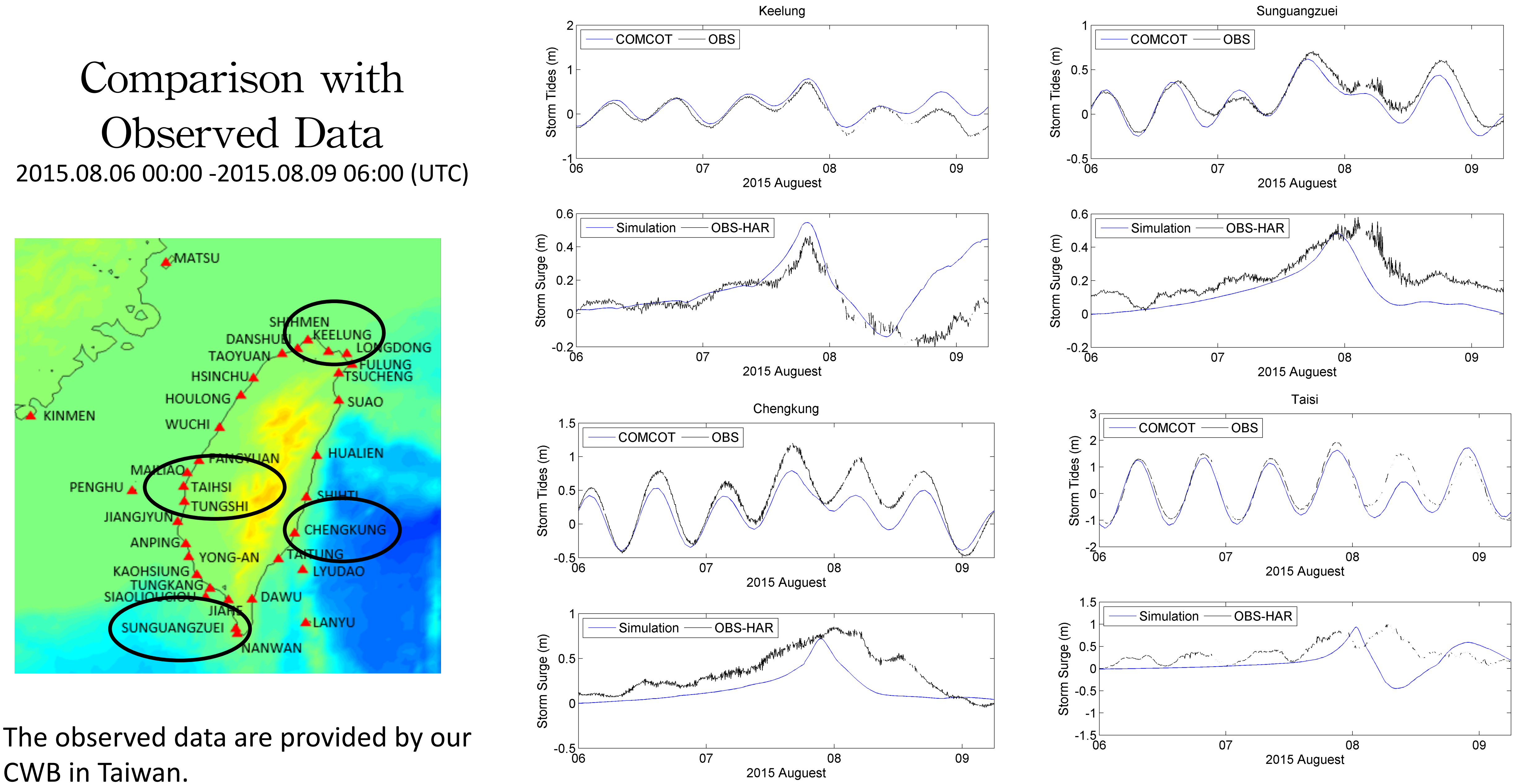




The large computational domain is adopted to simulate the complete storm surge propagation on spherical coordinate system.

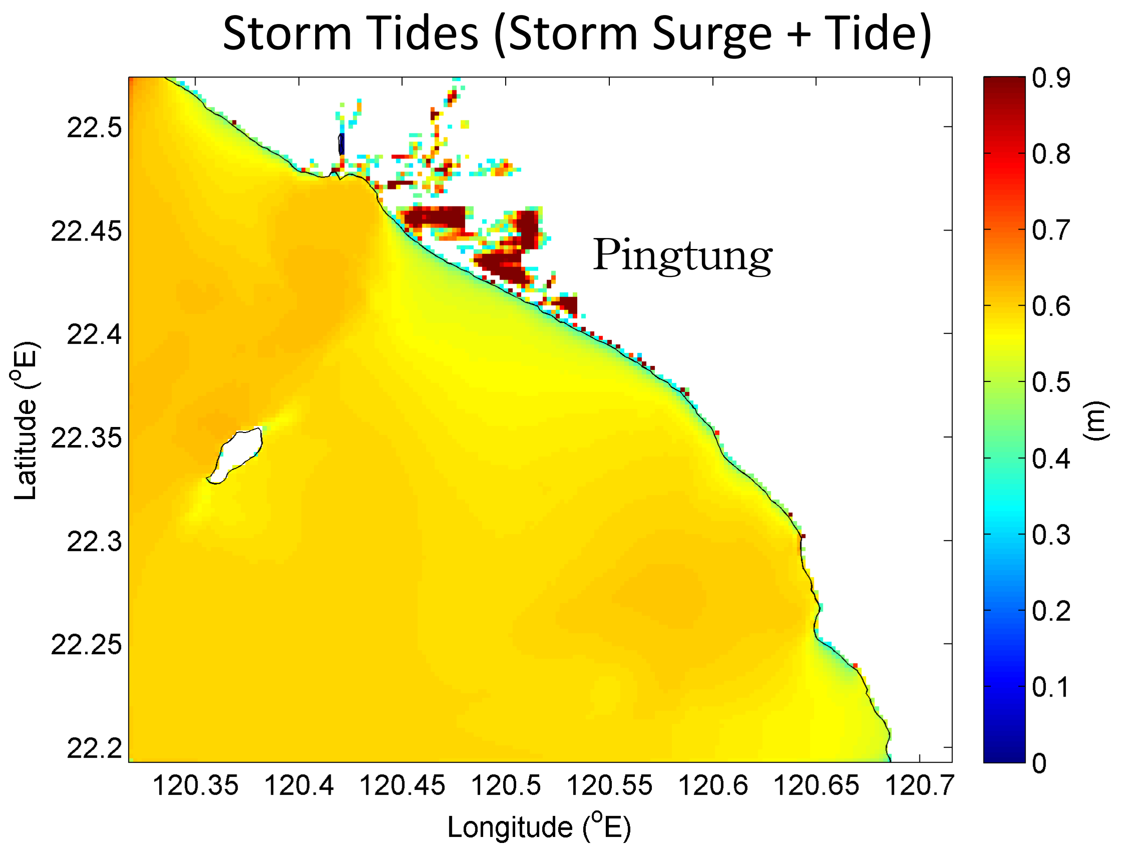
Comparison with Observed Data

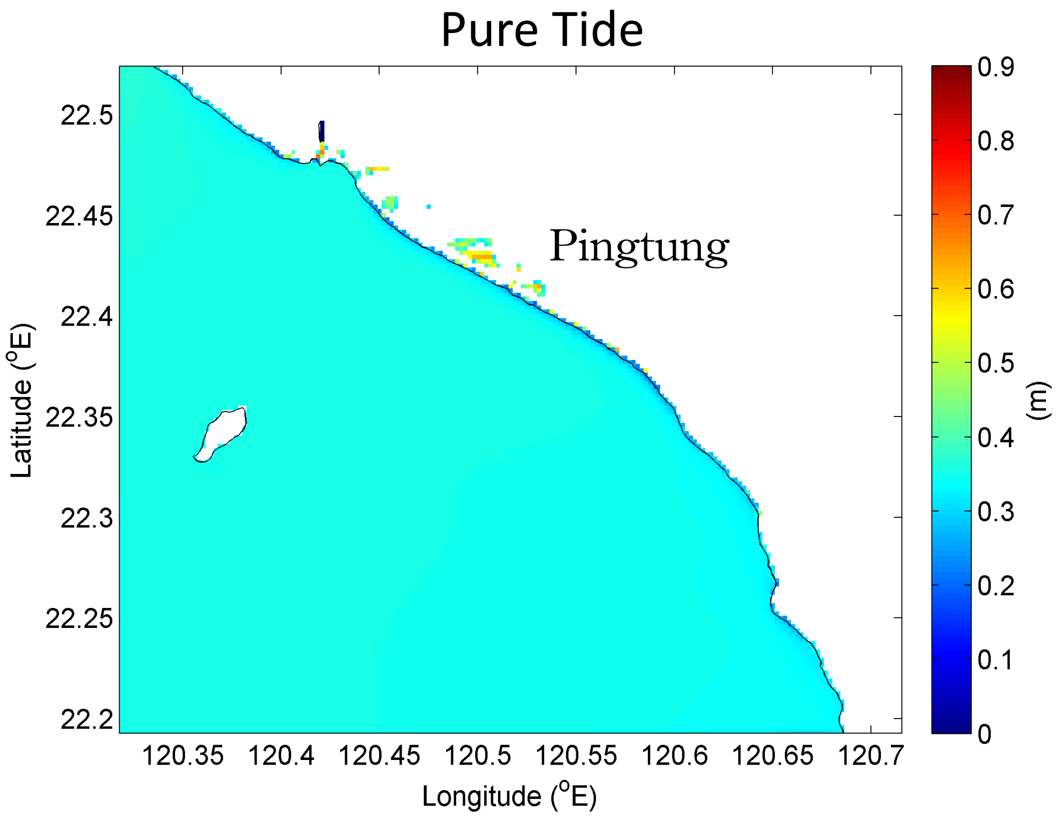
2015.08.06 00:00 -2015.08.09 06:00 (UTC)



The observed data are provided by our CWB in Taiwan.

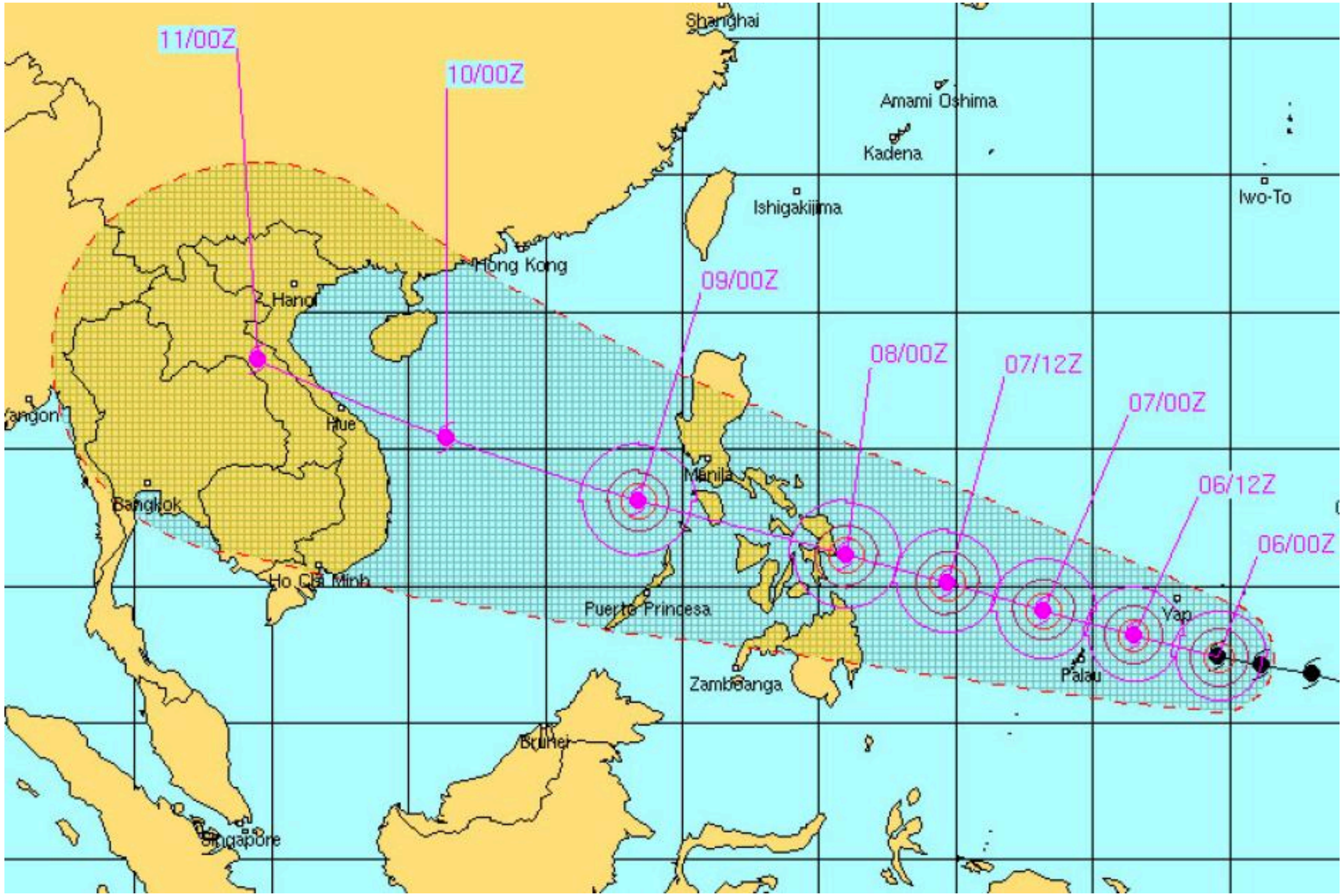
Coastal Inundation Calculation



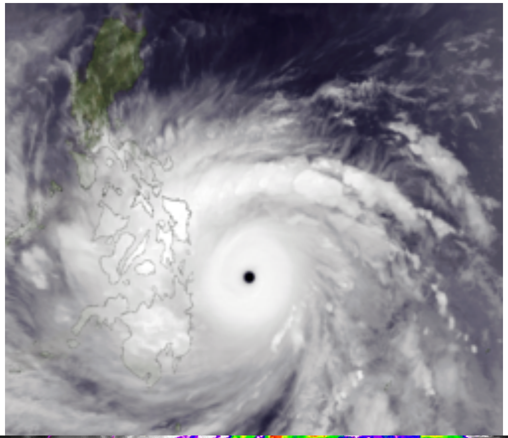


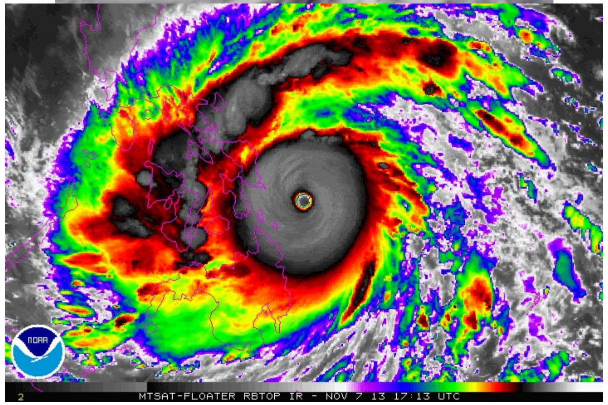
Our COMCOT storm surge model could also calculation the inundation area with nonlinear shallow water equations which considers nonlinear effects, bottom effects, and Coriolis effects inside.

The Case Study of 2013 Typhoon Haiyan



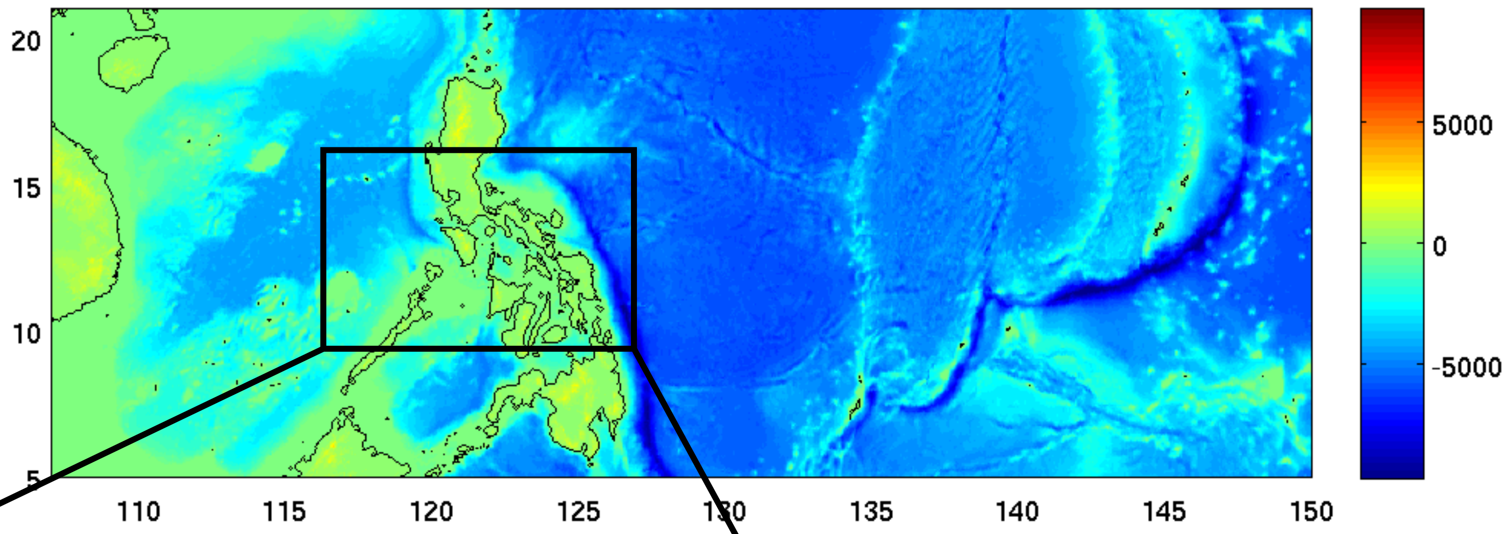
(Copyright: The US Joint Typhoon Warning Center)



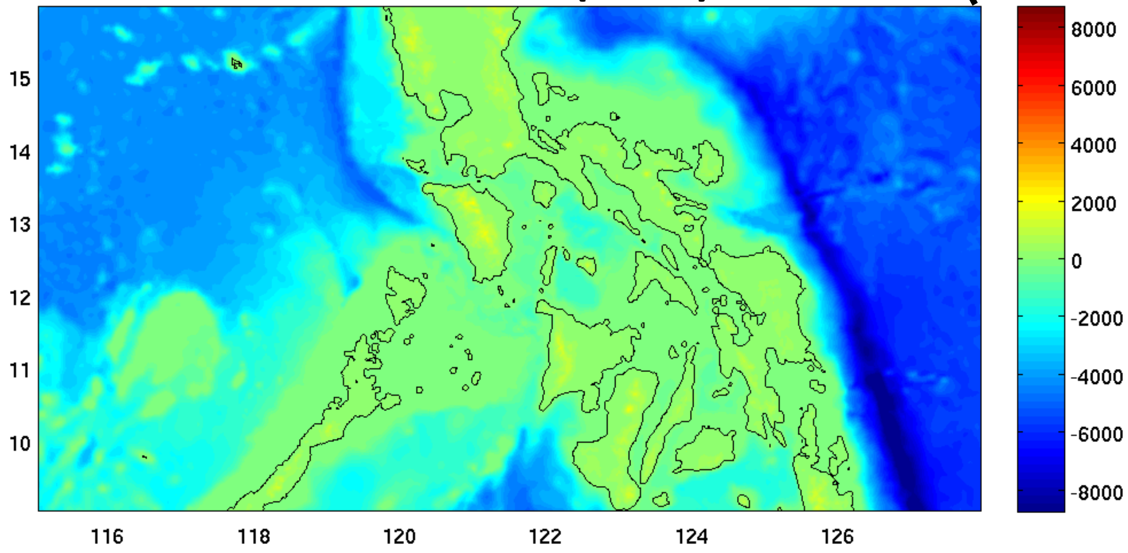


Nested Computational Domain

LAYER 01 (4 km)



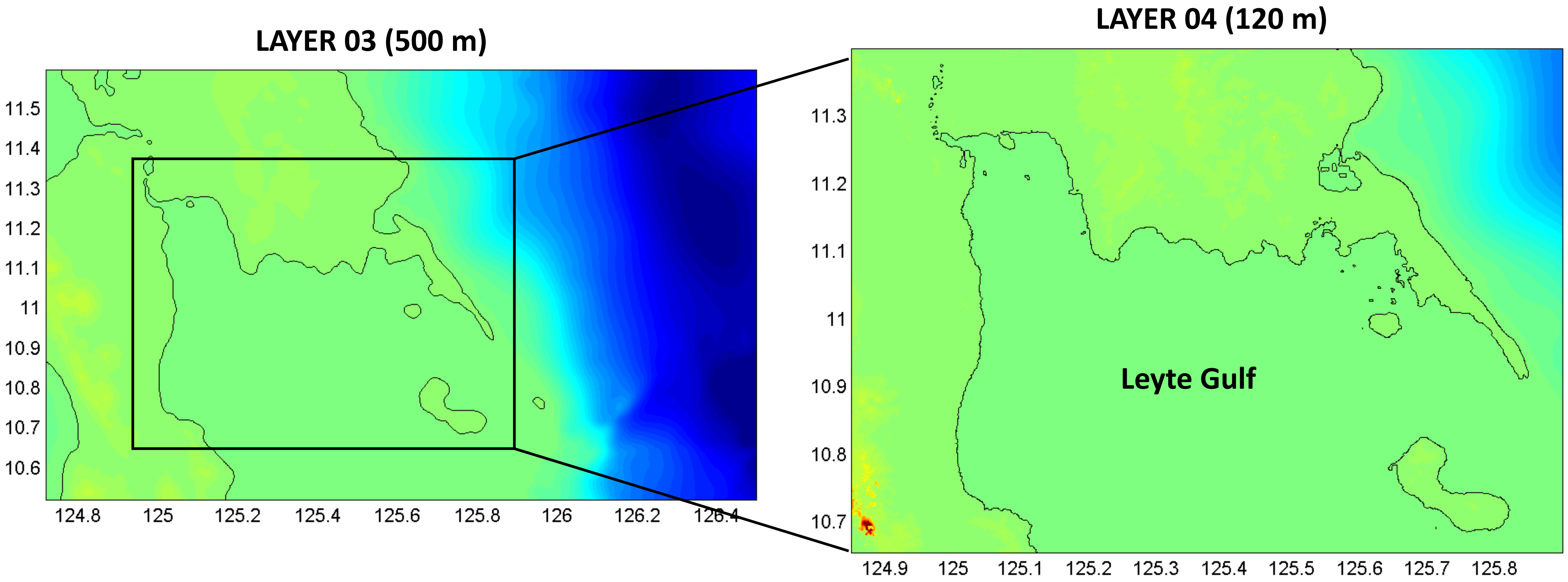
LAYER 02 (1 km)



- Layer 01 can cover the complete typhoon life cycle of Typhoon Haiyan and the full storm surge propagation.

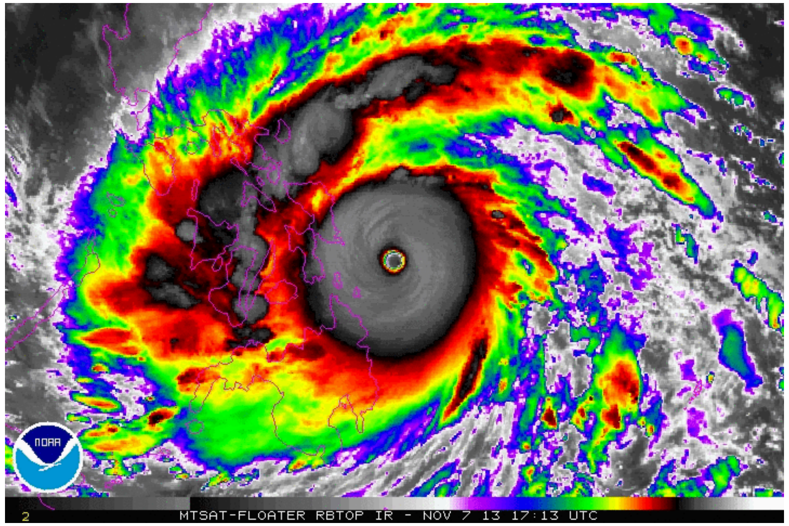
- Layer 02 can include the offshore hydrodynamic progresses of storm surge on the fine mesh domain.

Near-shore Computational Domain



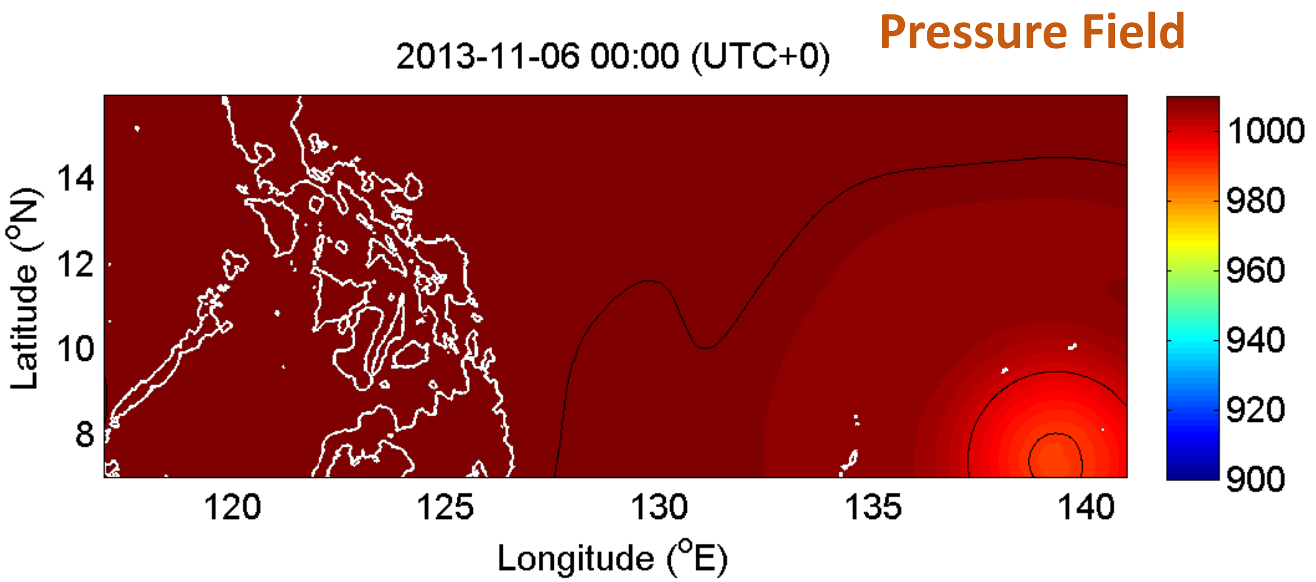
The computational domain of Layer 03 and Layer 04 could cover the storm surge propagations in offshore and nearshore regions.

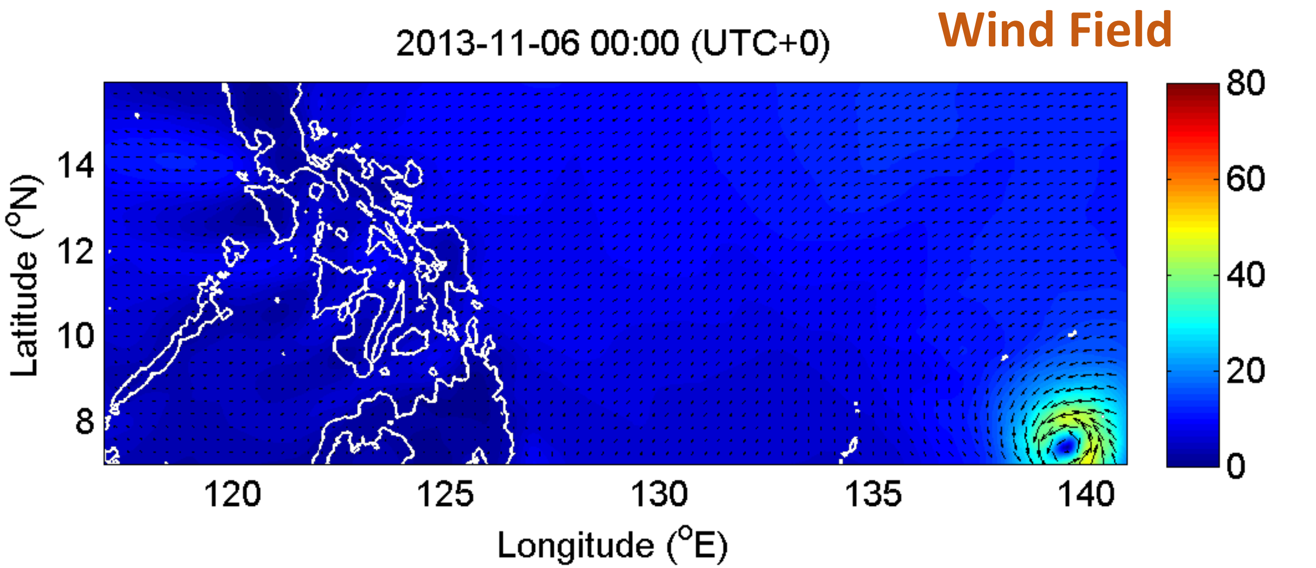
Couple with the Atmospheric WRF Model



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

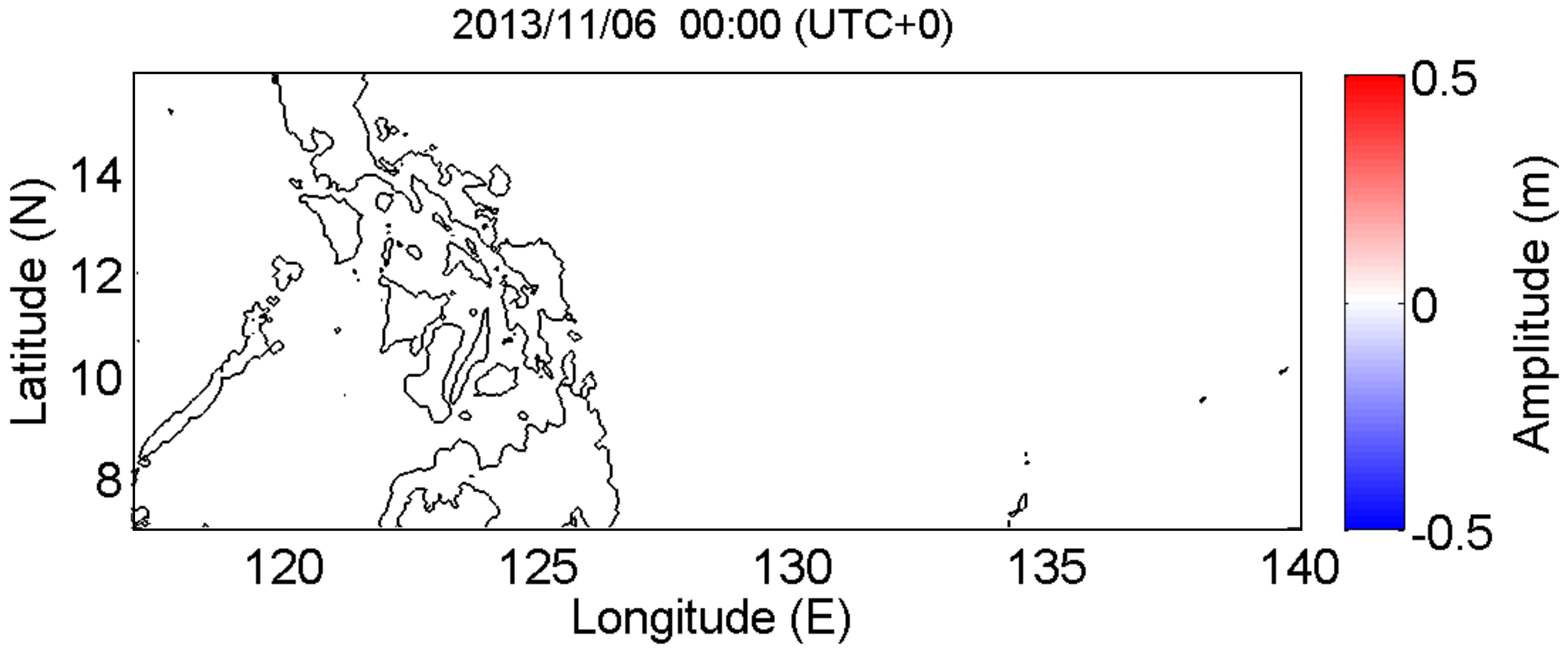
The WRF simulations are provided by Dr. Chuan-Yao Lin, AAR Modeling Laboratory (Sinica).





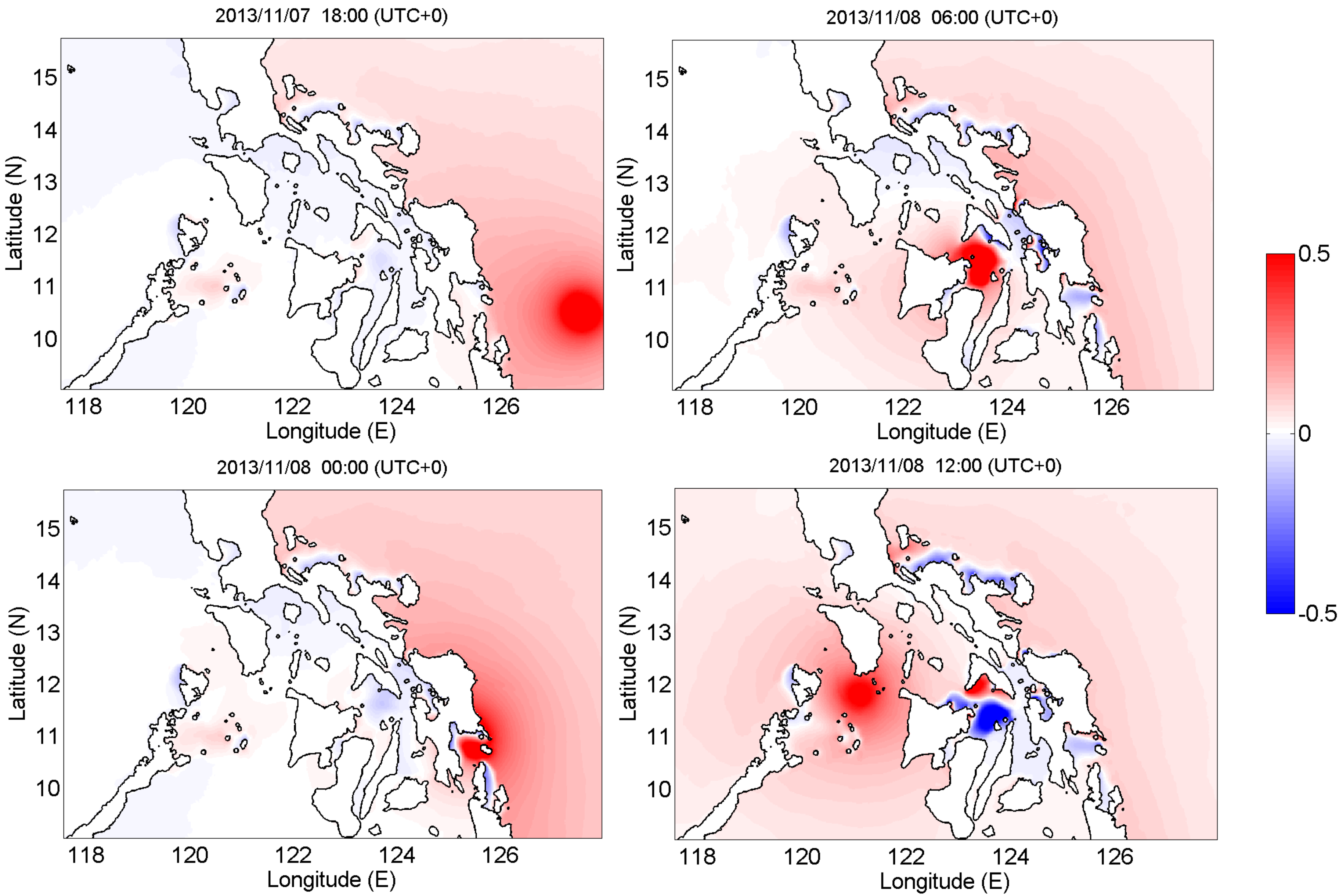
Storm Surges Induced by Typhoon Haiyan

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

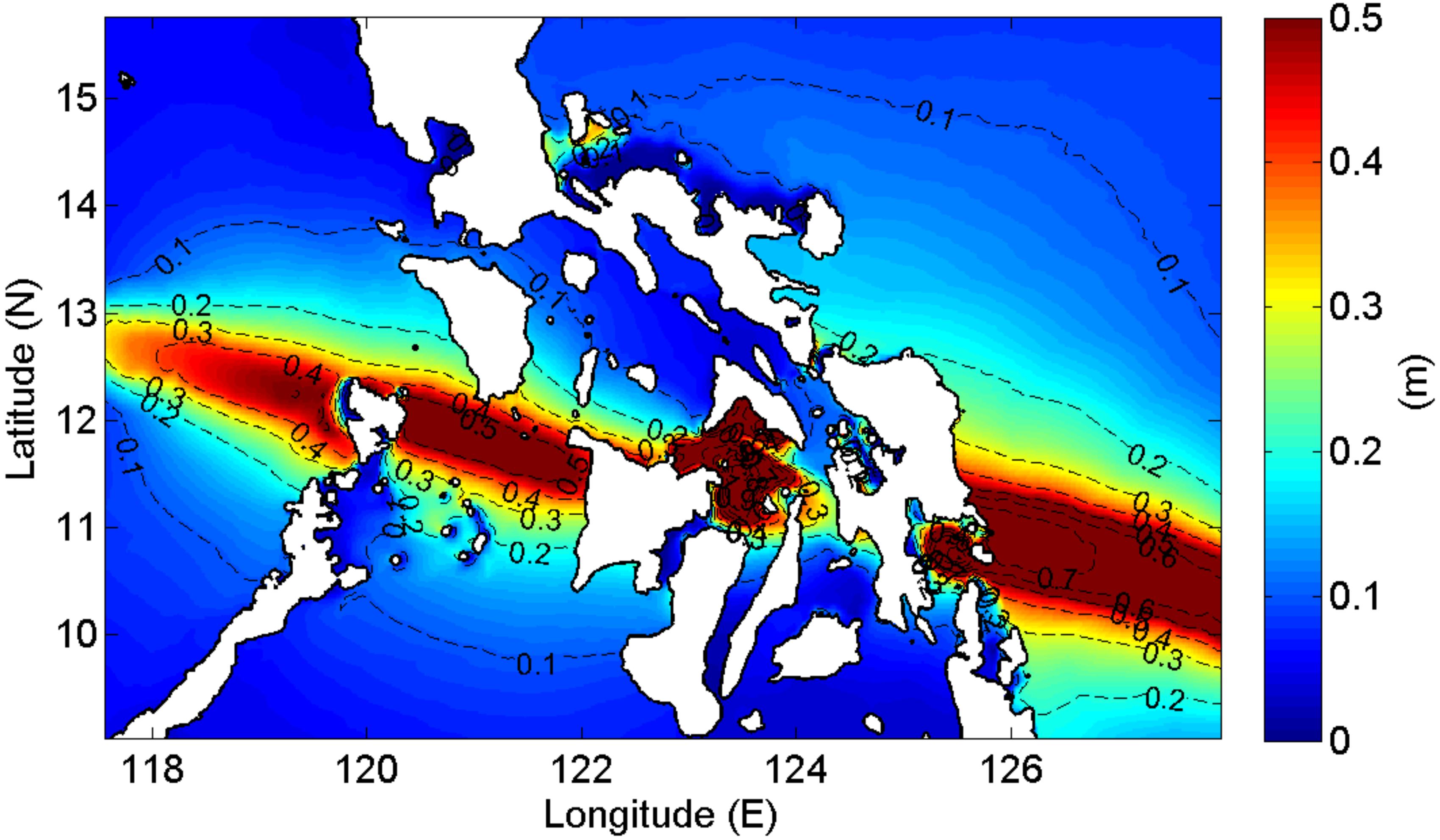


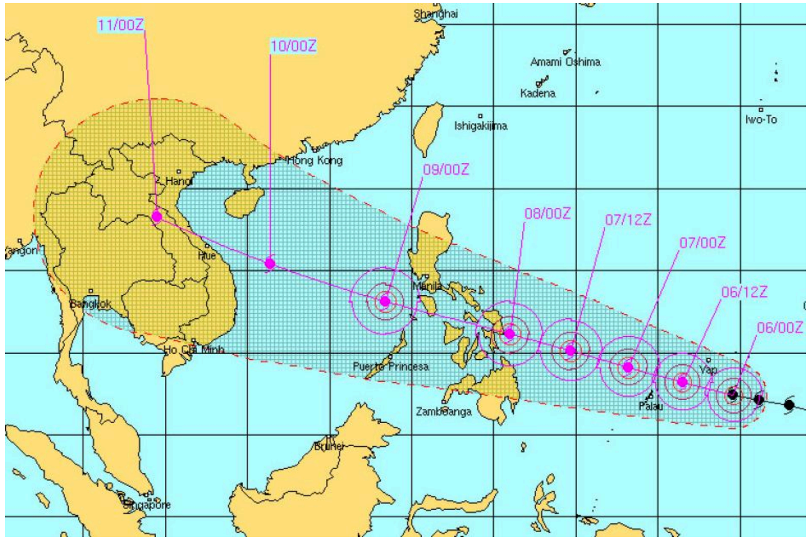
Large computational domain to cover the complete storm surge propagation induced by Typhoon Haiyan with Coriolis effect.

Snapshots of Storm Surges in the Philippines



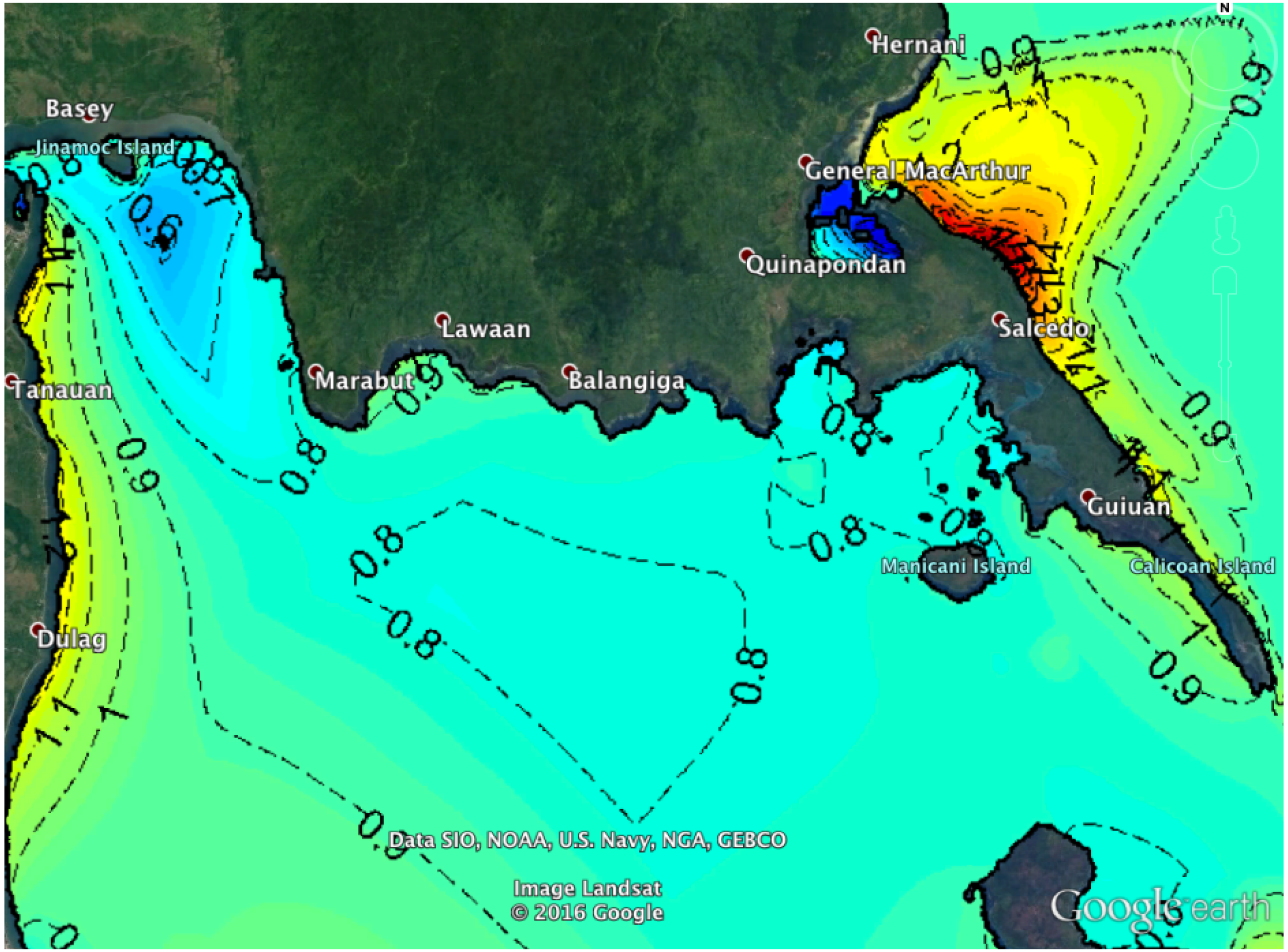
The Maximum Storm Surges in the Philippines





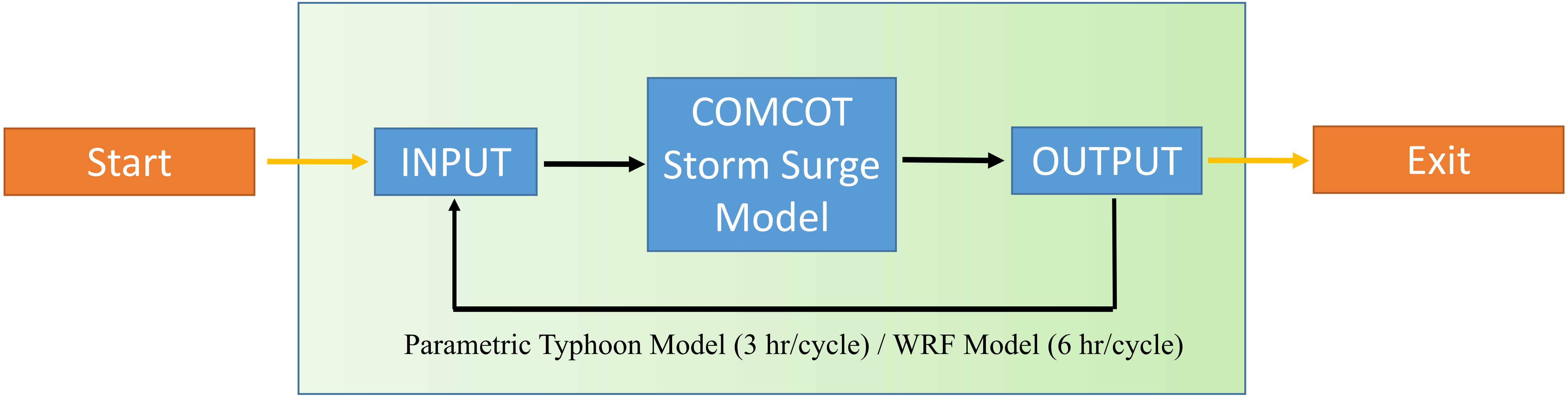
(Copyright: The US Joint Typhoon Warning Center)

Maximum Simulated Storm Tides at Leyte Gulf



Taiwan Storm Surge Operational System

Our COMCOT storm surge model has been the official operational system at the Central Weather Bureau this year.



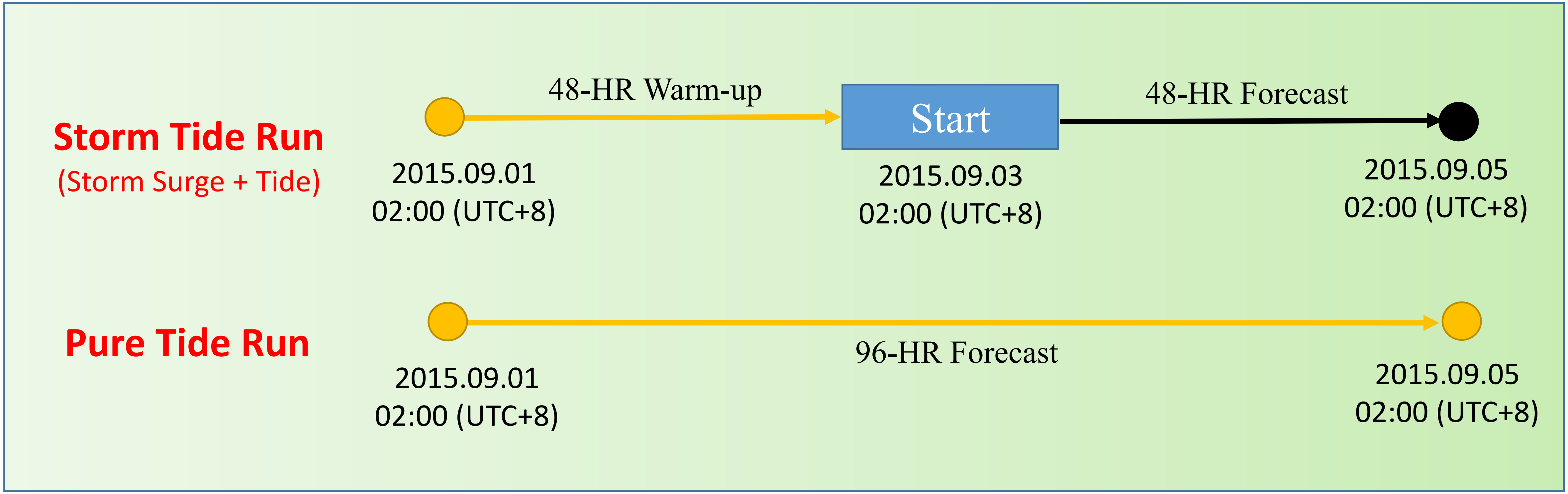
INPUT

- Meteorological Force: Parametric Typhoon Model or WRF Model.
- Tidal Boundary Condition: TPXO 7.1 model.

OUTPUT

- 48-HR Time Series for Storm Tide and Pure Tide at 34 specified locations.
- 2-dimensional model product.

Schematic Diagram for
Storm Tide Run and Pure Tide Run

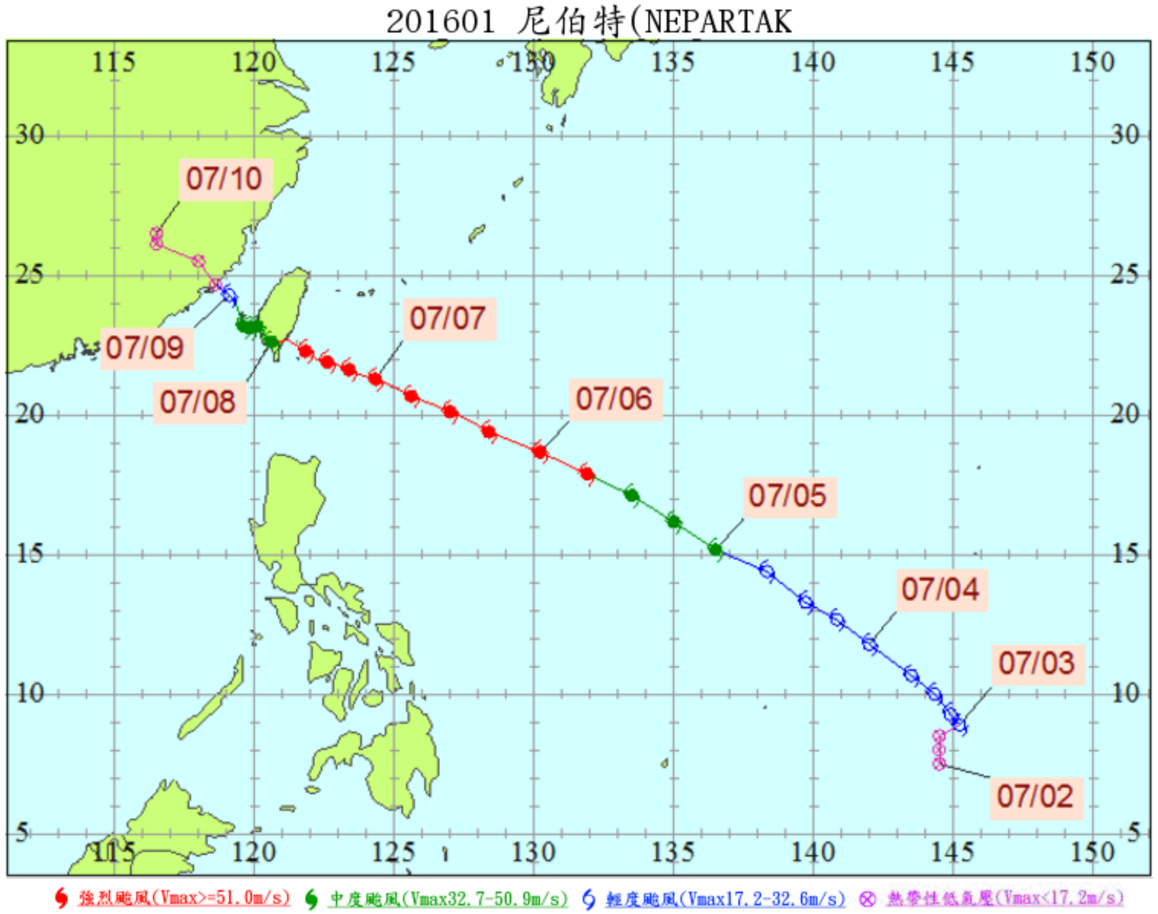


1. Every forecasting includes two 96-HR computations, and one for storm tide (storm surge + tide) run and another for pure tide run.

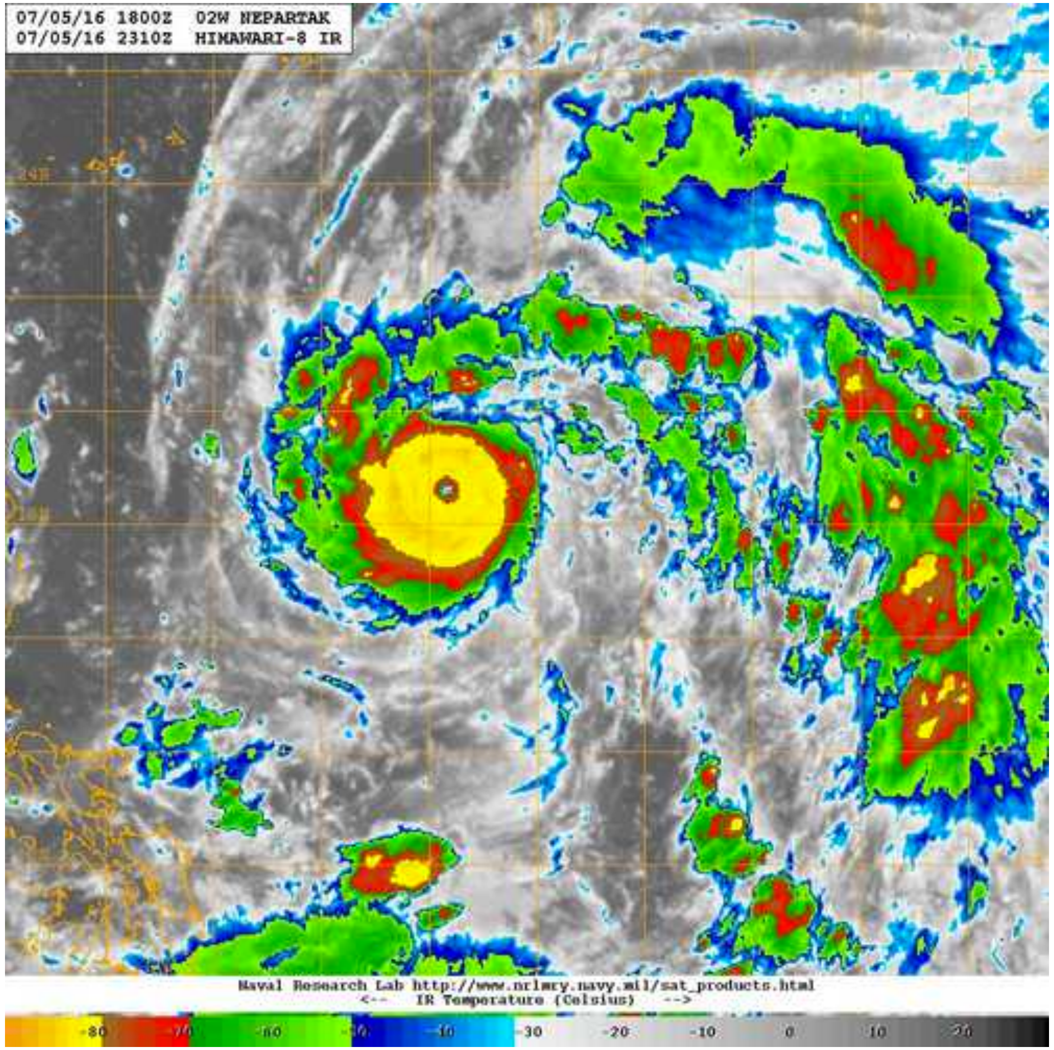
2. There are 48-HR warm-up and 48-HR forecast at each storm tide run.

2016 Catogory-5 Typhoon Nepartak in Taiwan

Our COMCOT storm surge model has been to the official operational system at CWB, Taiwan since Typhoon Nepartak.

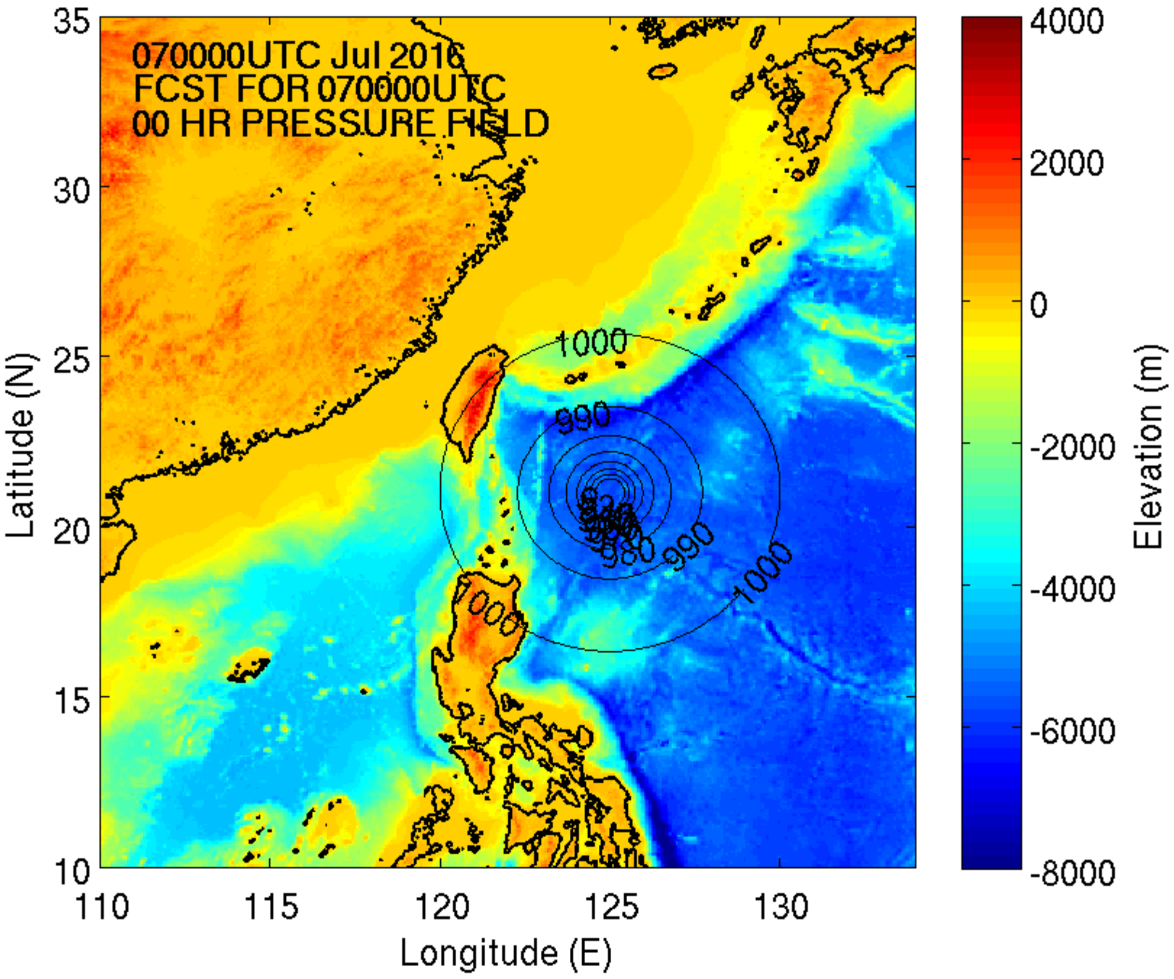


The track of Typhoon Nepartak (CWB, Taiwan)

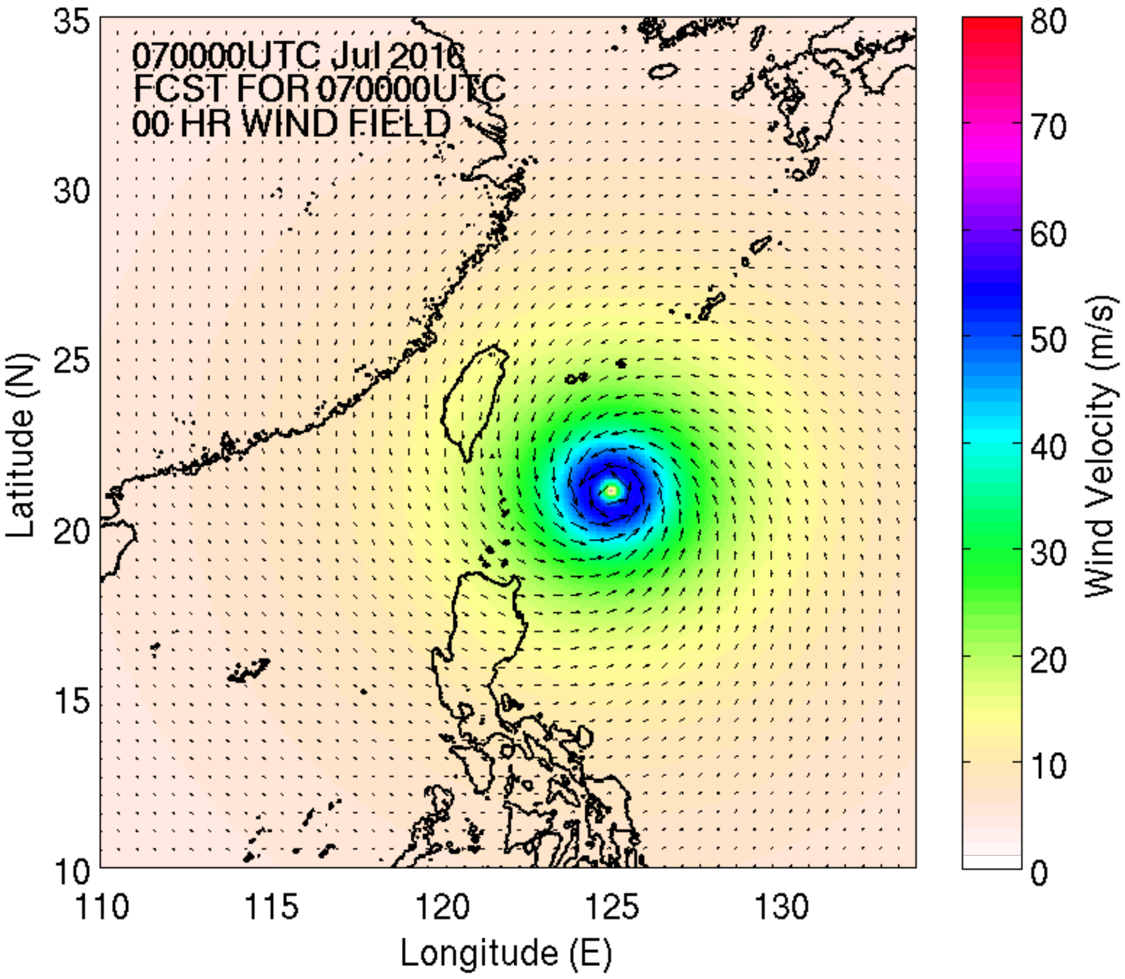


U.S Naval Research Laboratory

Meteorological Fields of Typhoon Nepartak

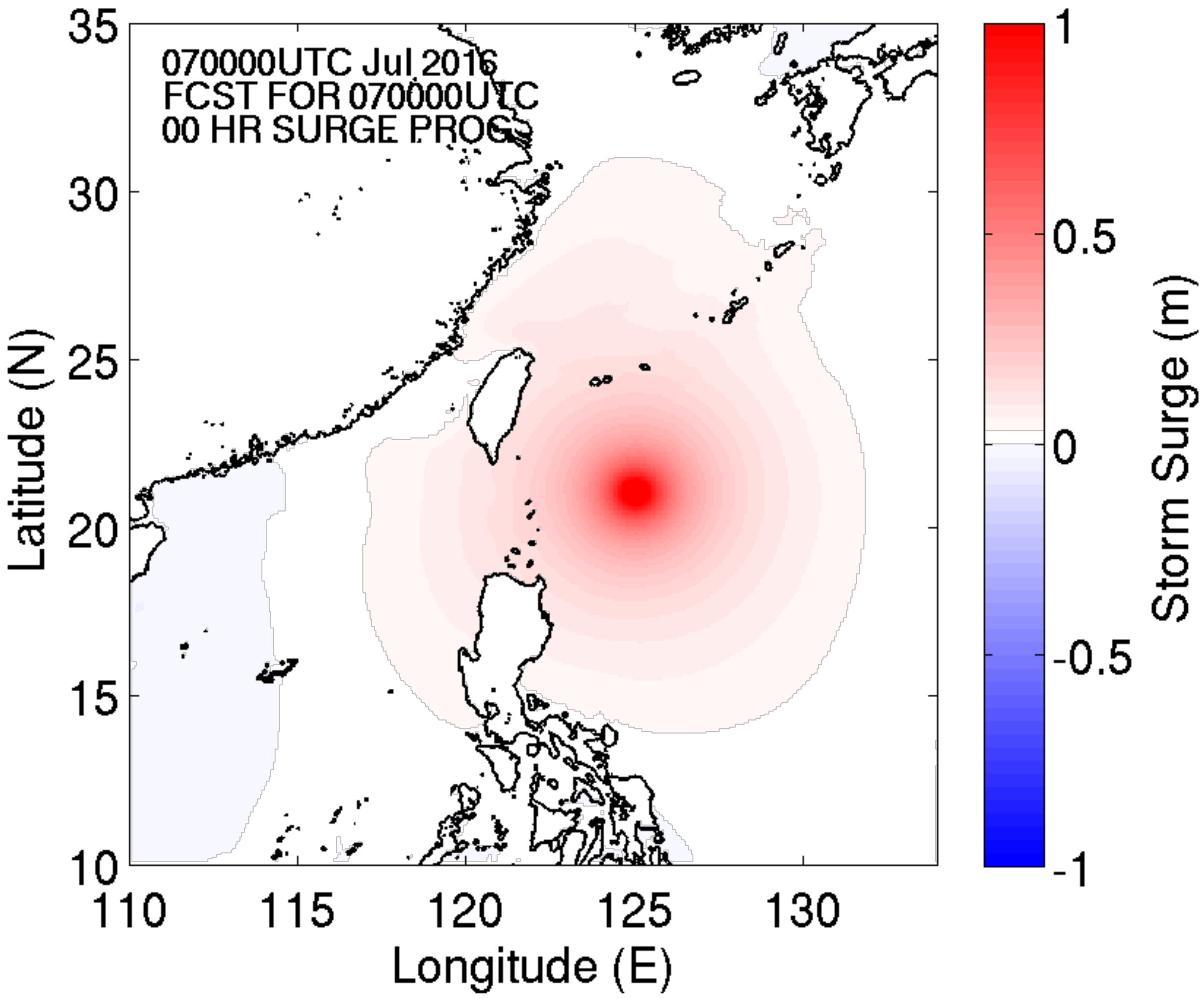


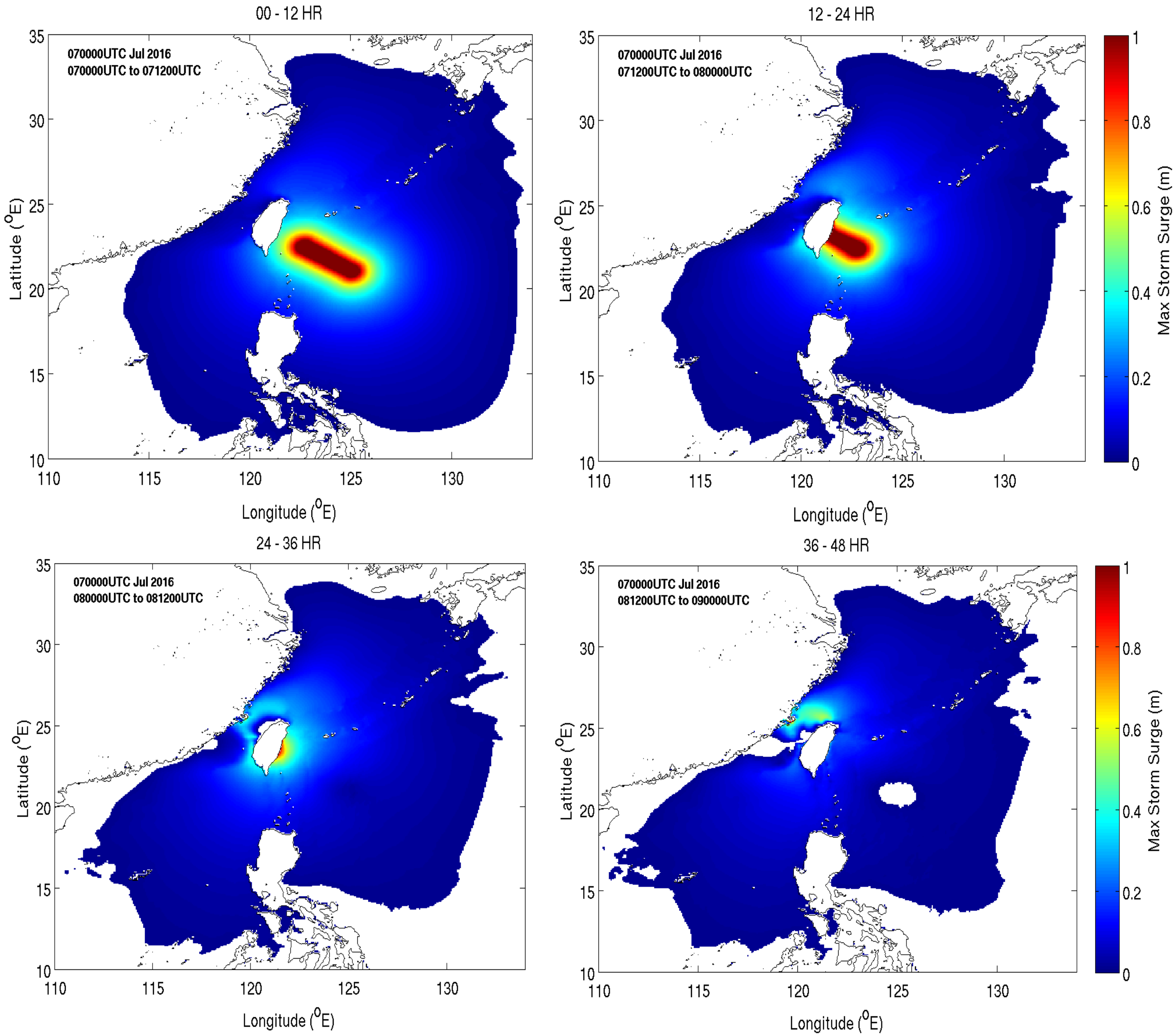
Pressure Field



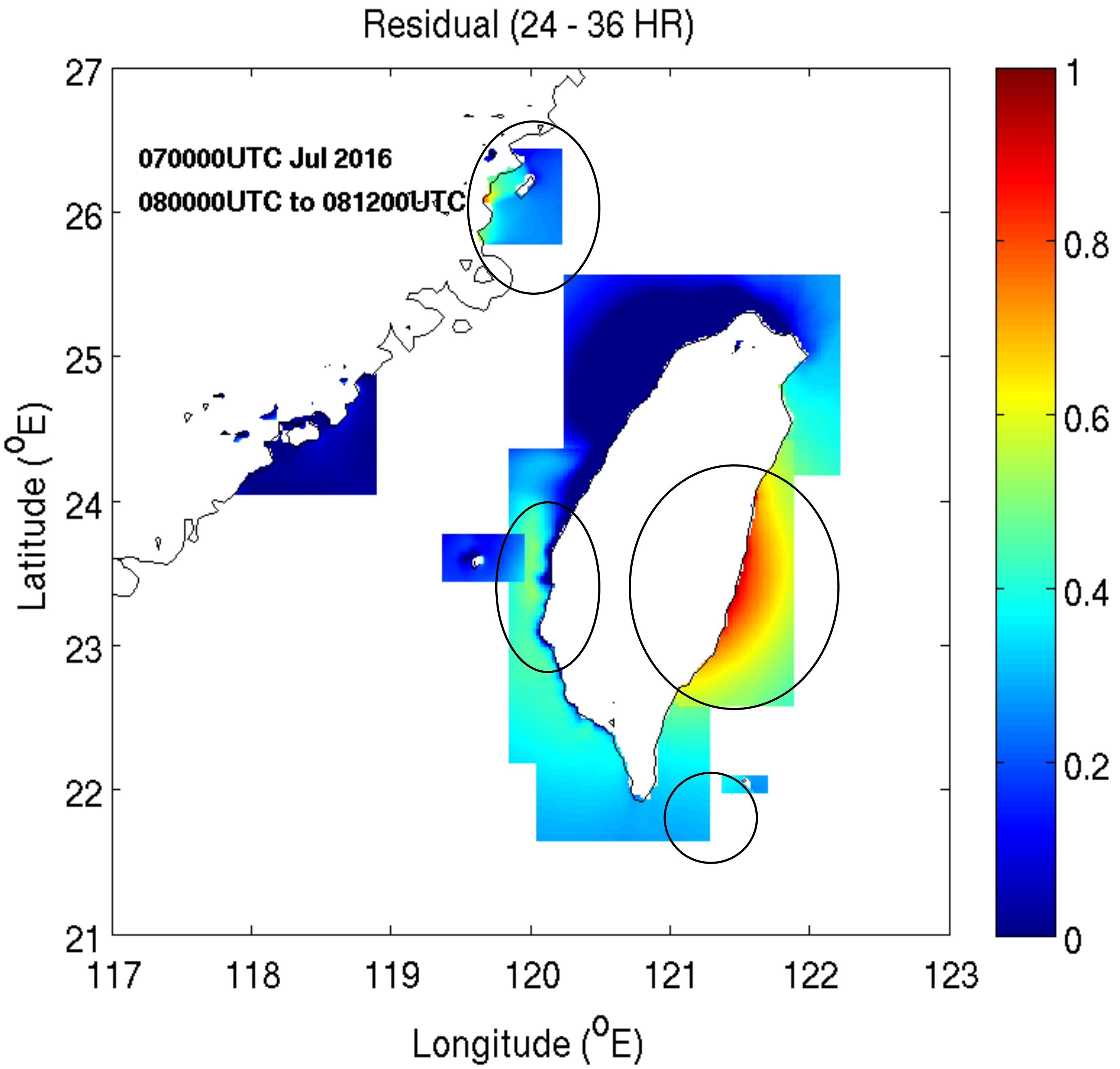
Wind Field

Storm Surges of Typhoon Nepartak





Storm surges could be calculated for 2-day predictions and only spends 1.0 hr on a PC-level computational resources.



Surge and Wave in Taiwan
(http://news.rthk.hk/rthk/ch/component/k2/1271353-20160708.htm)

People live in these areas need to pay attention to the storm surge inundation.

Conclusion

- Our COMCOT storm surge model :

✓ Adopt the **large computational domain** to cover the complete typhoon life cycle and full storm surge propagation.

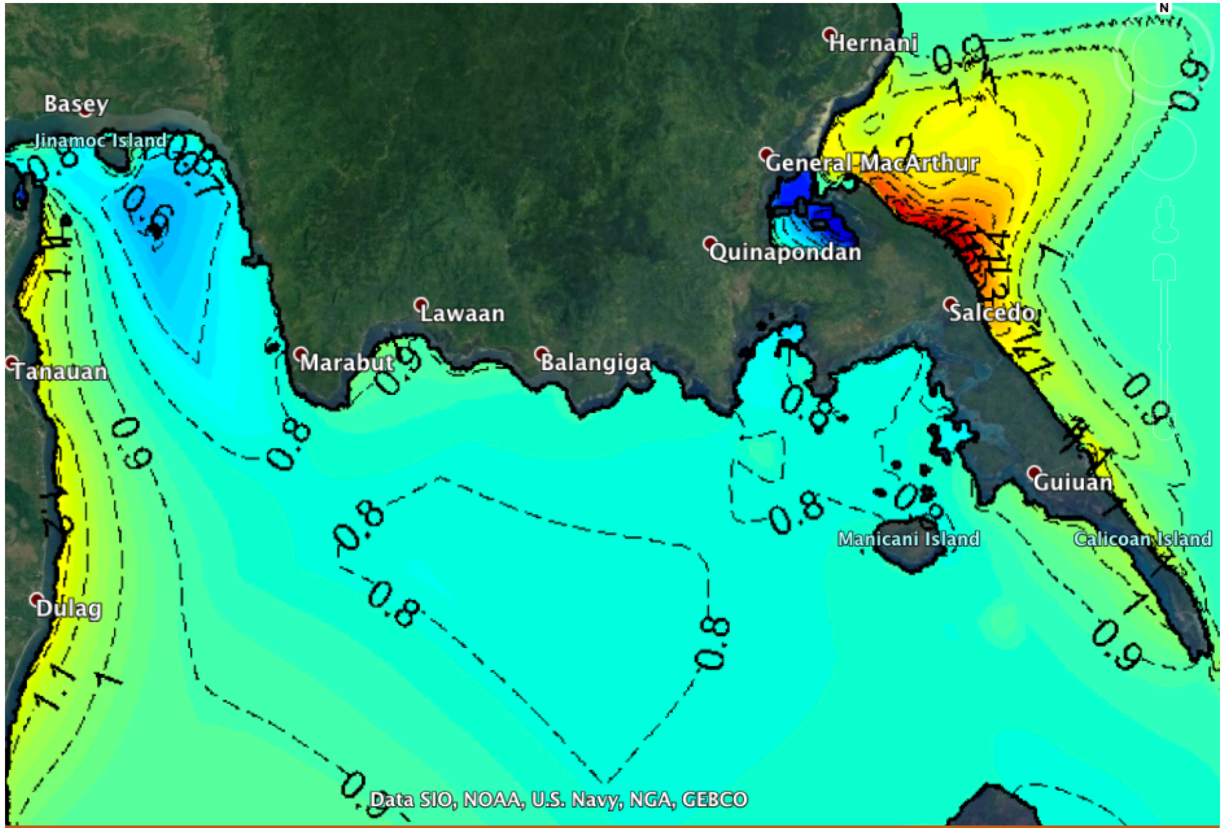
✓ Couple with the **dynamic atmospheric WRF model**.

✓ Couple with the **global TPXO tidal model**.

✓ Calculate **high-resolution storm surge inundation**.

✓ High-speed calculation for the **operational system**.

✓ It has been the **official** operational system at the Central Weather Bureau this year

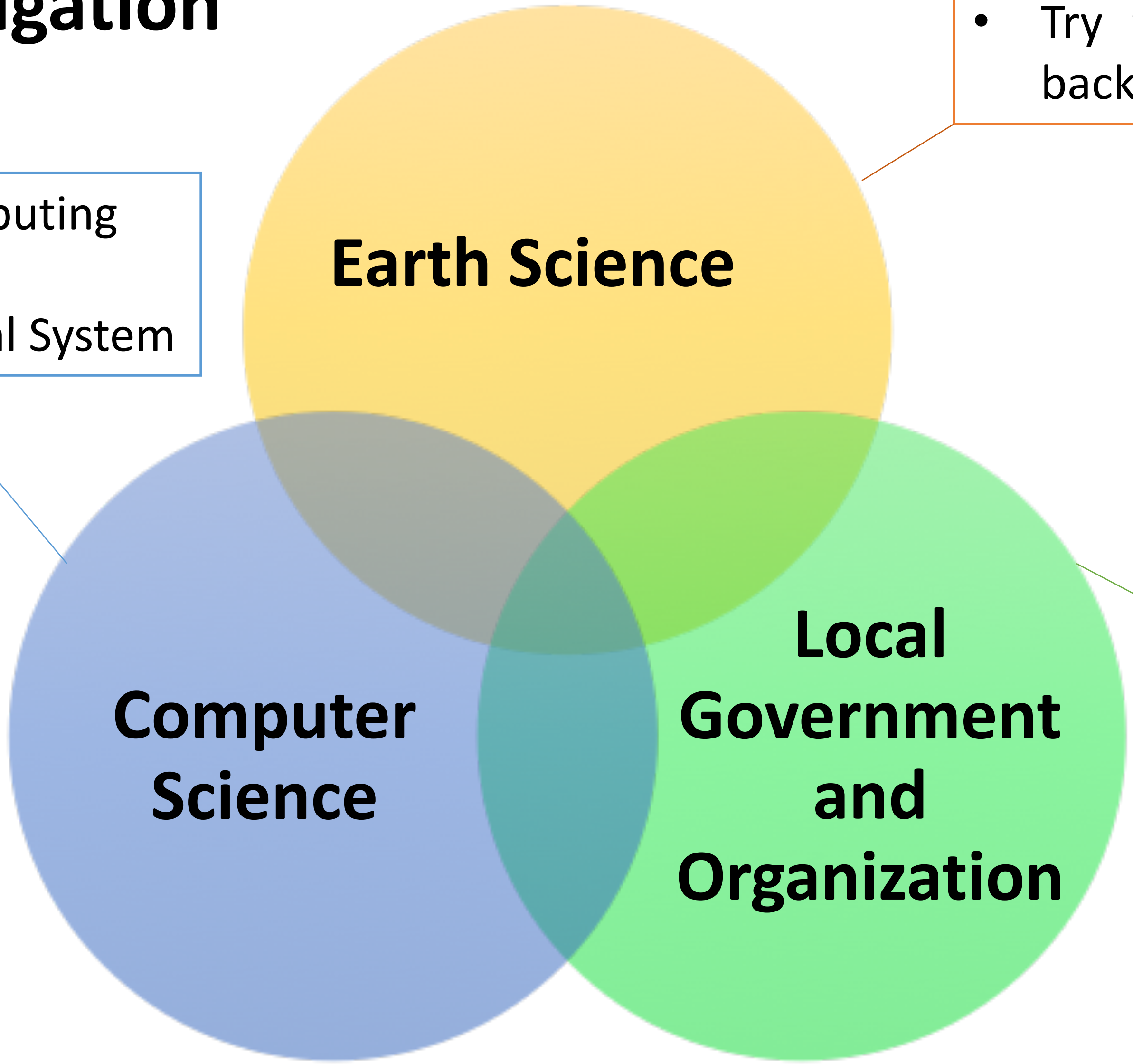


Maximum Simulated Storm Tides at Leyte Gulf, Philippines.

Integrated System for Disaster Mitigation

- Hydrodynamic modelling
- Aerodynamic modelling
- Try to understand the physic background of storm surge

- High Performance Computing
- Data Communication
- Storm Surge Operational System



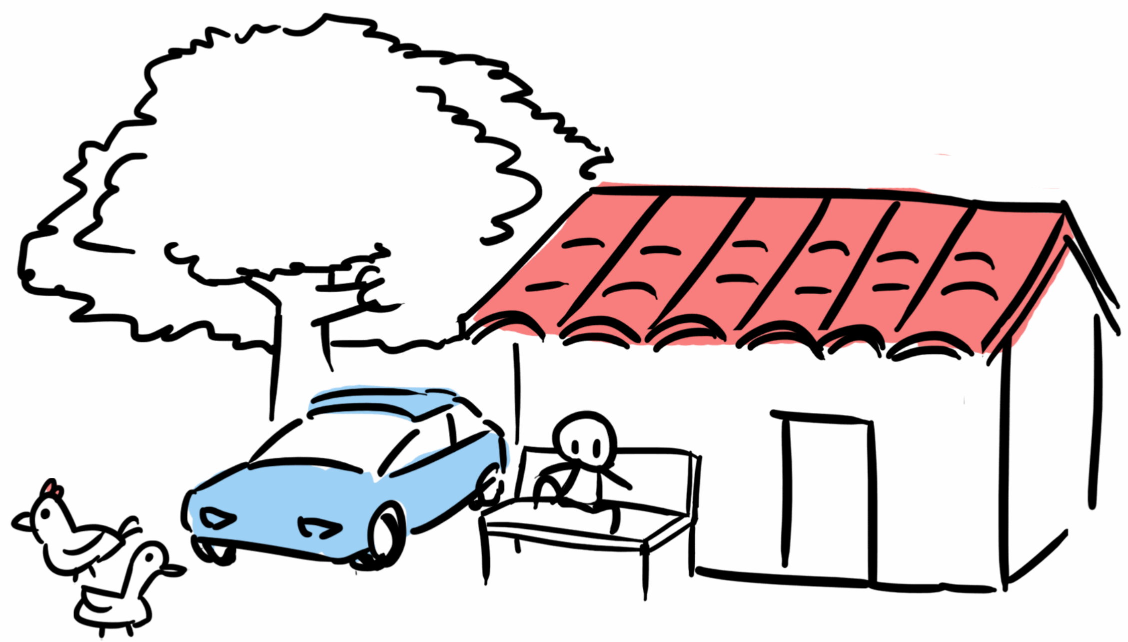
- Local Observed data
  - Tide Gauges
  - Inundation Area
  - Doppler Data
  - Meteorological Data
- Bathymetry data

Before the happened of storm surge:

1. Prepare the operational storm surge model and make sure that is could be used when typhoons are coming.
2. Web-portal service and forecast products.

After the disaster of storm surge:

1. Integrate the local observed data for model validations.
2. Try to understand the physics of storm surge and associated behavior from case studies.



Thanks for your listening.

Welcome comments and discussion.

Yu-Lin Tsai,
National Central University (Taiwan)

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Tsunami Science Laboratory

ASGC TWGrid