Disaster Mitigation Workshop
APAN 44 at Dalian, China

Development of Fast-Calculation Storm Surge System and Case Study of 2013 Typhoon Haiyan/Yolanda

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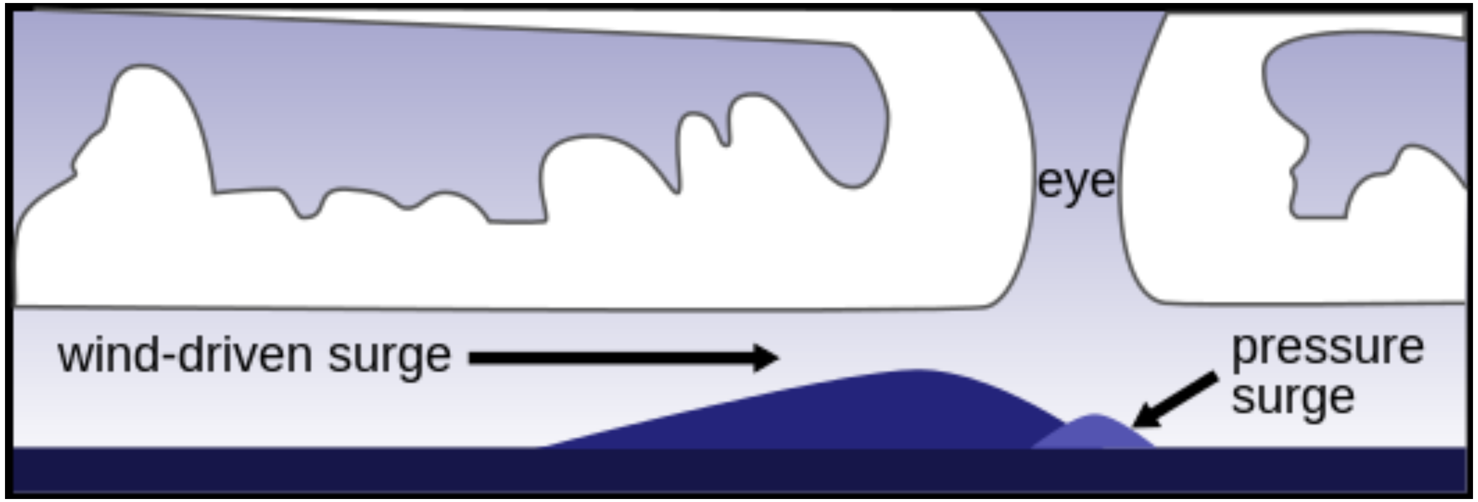
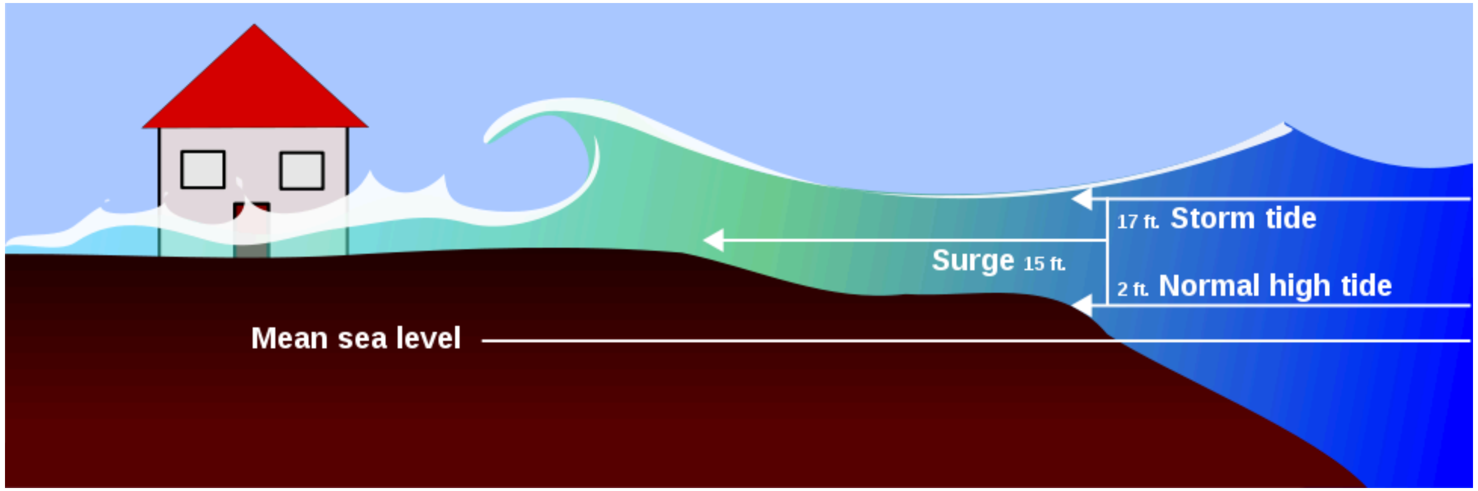
STORM SURGE



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

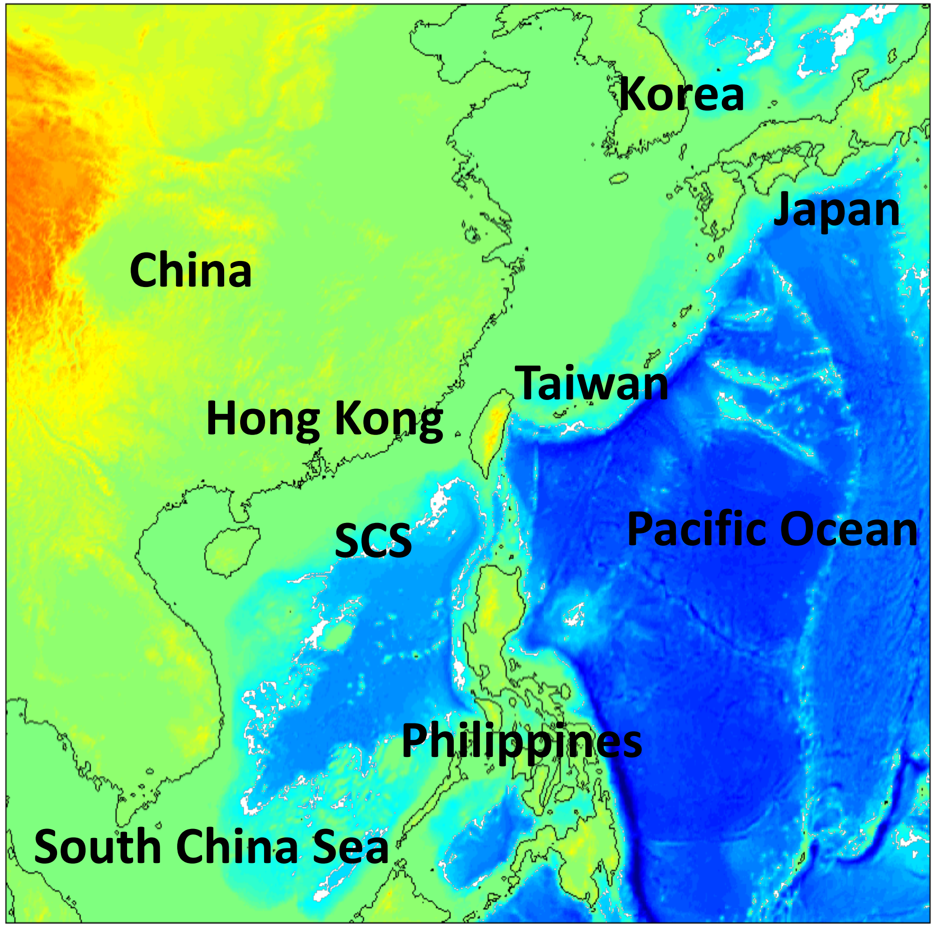
- *Destroy of homes and business*
- *Potential threat of coastal communities*
- *Damages of roads and bridges*

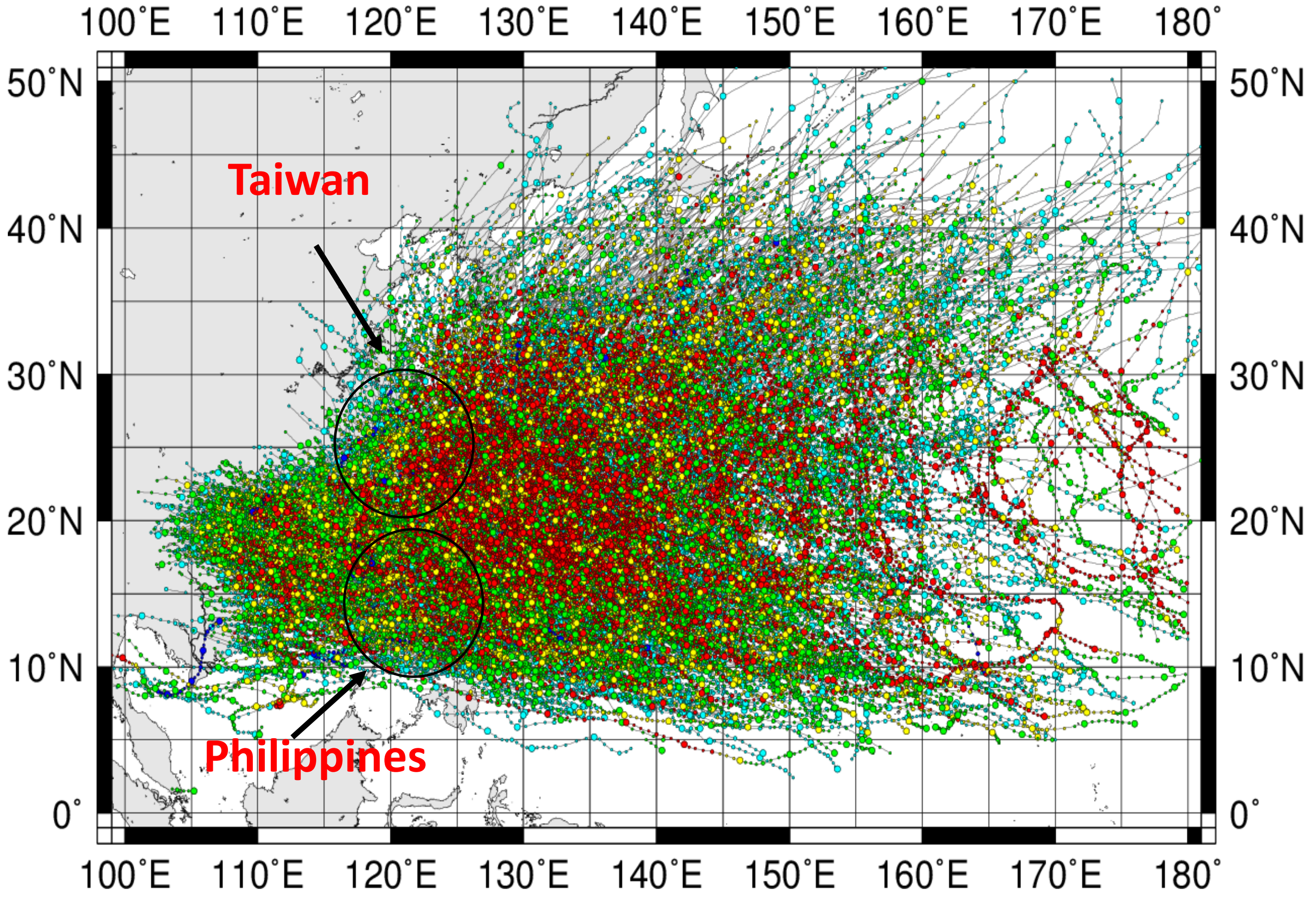
Views of inundated areas in New Orleans following breaking of the levees surrounding the city as the result of storm surge from Hurricane Katrina - 2005

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

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

Tropical Cyclones in East Asia

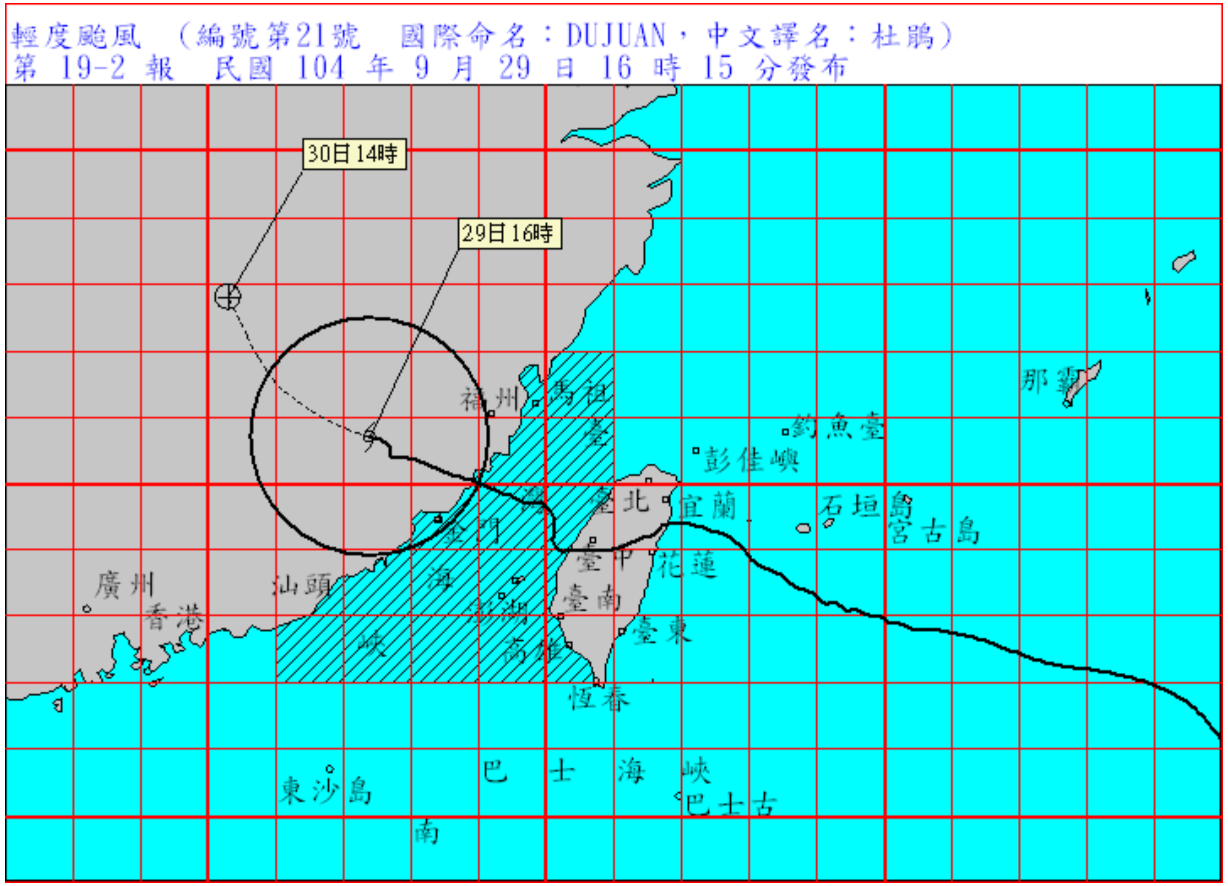




Tracks of all tropical cyclones in the northwestern Pacific Ocean between 1951 and 2014.

Taiwan – Catogory-4 Typhoon Dujuan

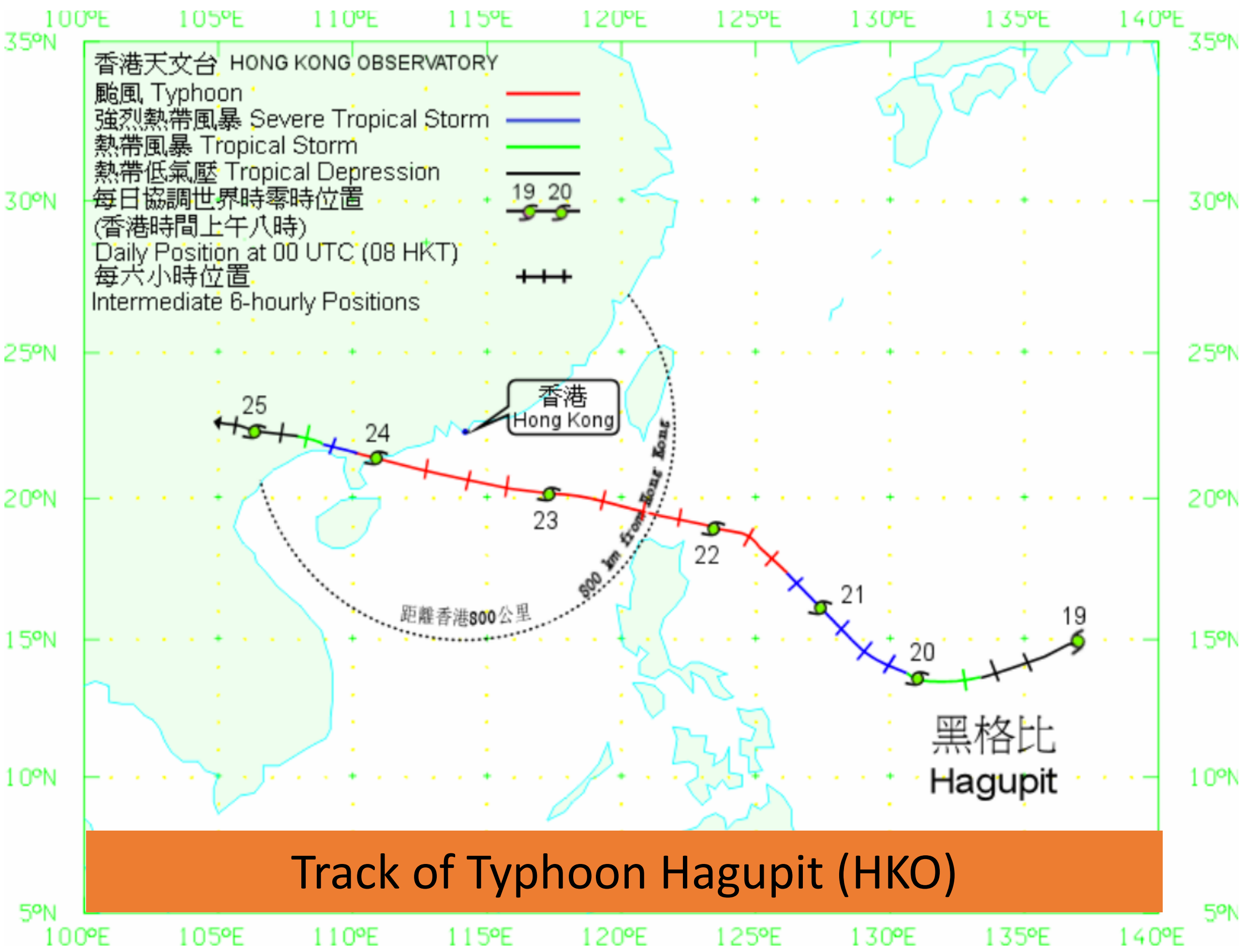
2015.09.15 – 2015.09.29



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

Hong Kong - Catogory-4 Typhoon Hagupit

2008.09.19 – 2008.09.25

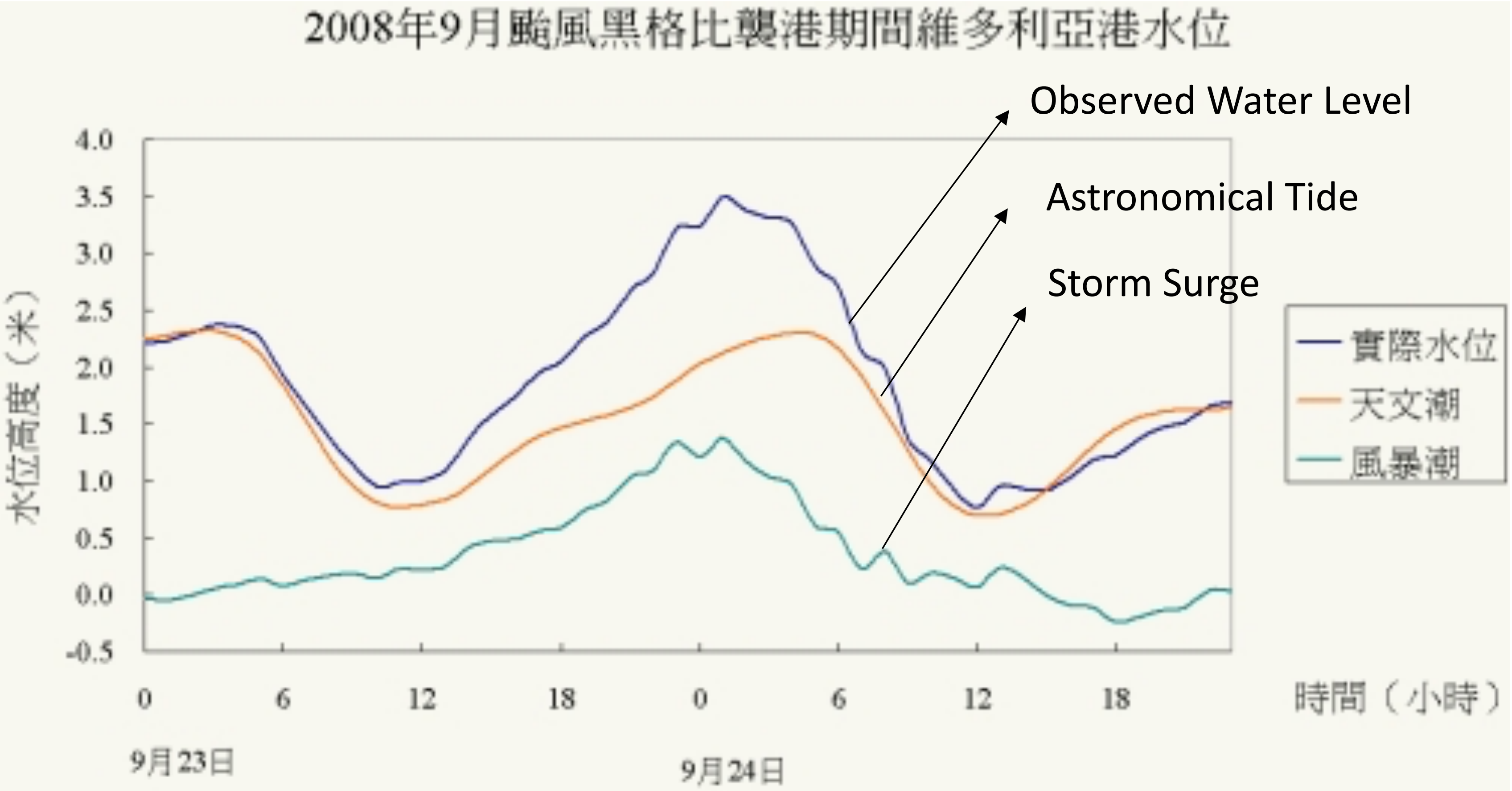


Track of Typhoon Hagupit (HKO)

Hong Kong Local News

Saltwater Intrusion

Records of Storm Surge at Victoria Harbour (Hong Kong)

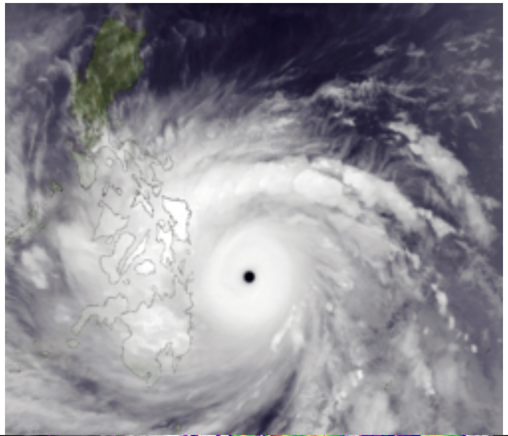


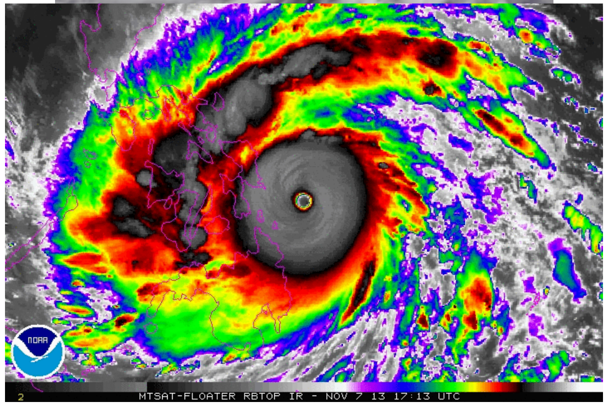
香港天文台 (Hong Kong Observatory)
http://www.weather.gov.hk/m/article_uc.htm?title=ele_00184

2013 Typhoon Haiyan/Yolanda 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.

Field Survey after Typhoon Haiyan

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

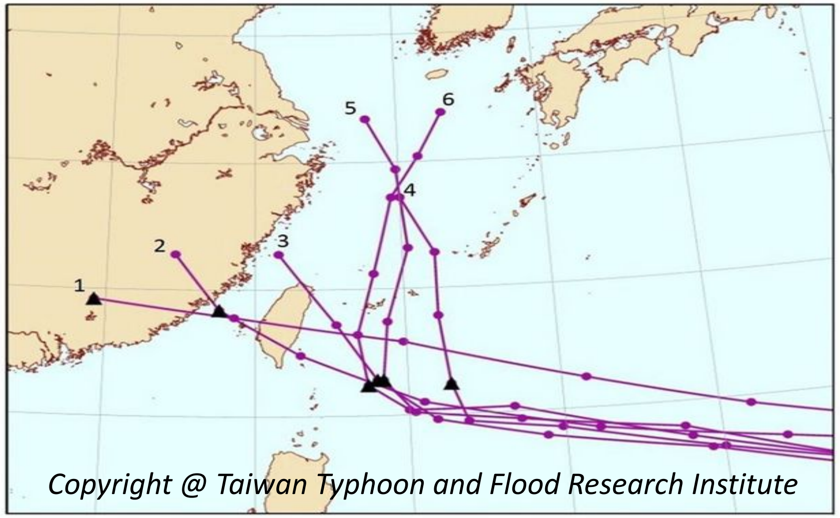
2) Sea wall damage at Tagpuro and the run-up height was about **6.9 m**.

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.)

Our Goals for a Storm Surge Operational System

- Adopt large enough spherical computational domain to cover the complete typhoon life cycle and full storm surge propagation.
- Include nonlinear calculation, bottom shear stresses and shoaling effects in near-shore regions.
- Consider multi-scale storm surge propagation in both open ocean and coastal regions.
- Calculate high-resolution storm surge inundation area for risk assessment.
- Combine with the dynamic atmospheric model.
- Combine with the global tidal model.
- High-speed efficiency for the early-warning system.



Uncertainty of Storm Tracks

Storm surge headed ashore.

Multi-Scale Storm Surge Propagation (NOAA)

The Introduction of CWB COMCOT-Surge Model

(**CO**rnell **M**ulti-grid **CO**upled **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 nonlinear 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.

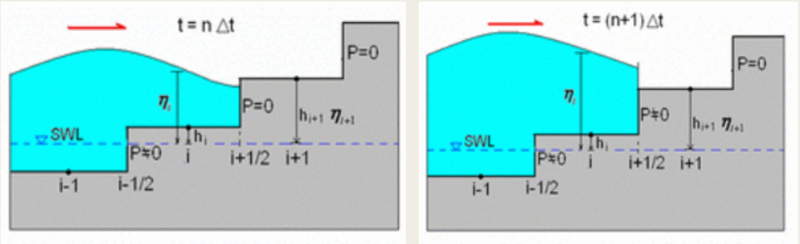


Fig.02 Moving Boundary Scheme

(1). NOAA Benchmark Problem Validation

Compare with the Solitary Wave Run-up Experiments (Synolakis, 1986 and 1987).

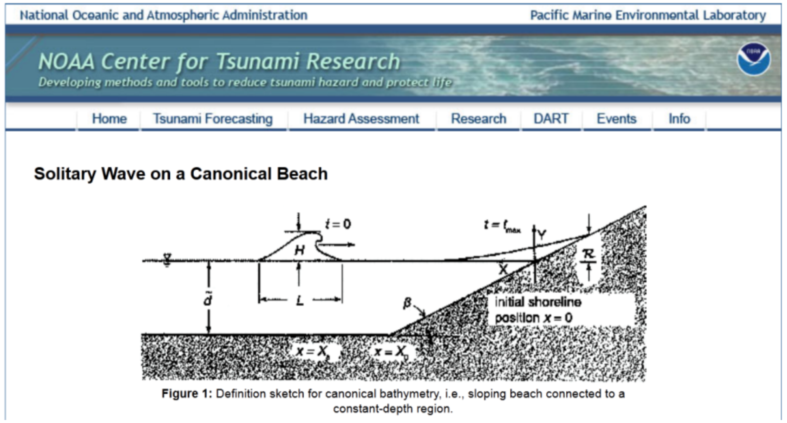
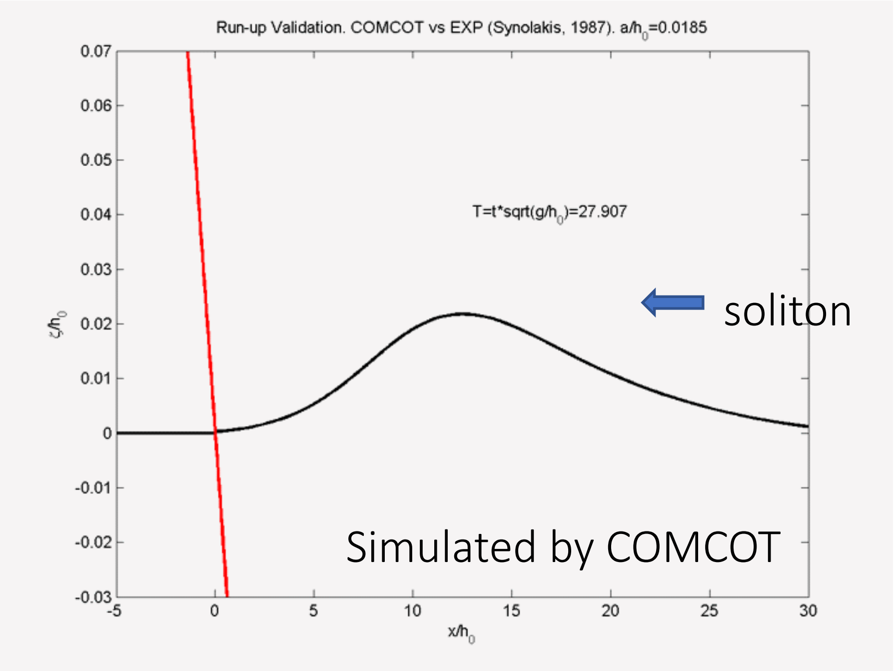
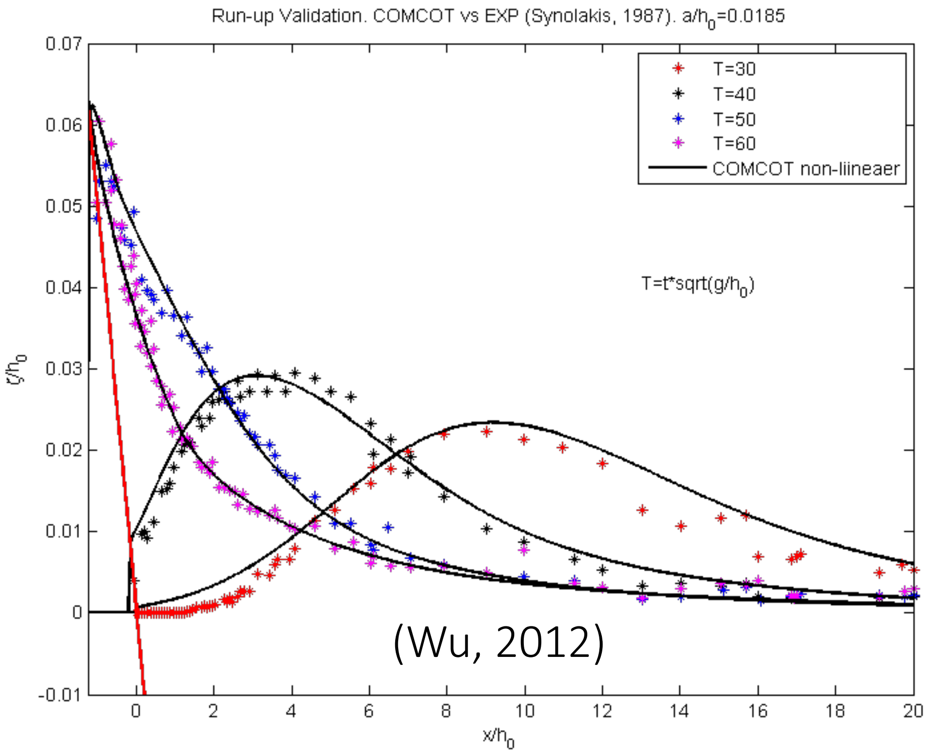


Figure 2: Time evolution of H = 0.0185 initial wave over a sloping beach with $\cot\beta = 19.85$ from $t = 25$ to 65 with 10 increments. Constant depth-segment starts at $X_0 = 19.85$. While markers show experimental results of Synolakis (1986, 1987), solid lines show nonlinear analytical solution of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

(from NOAA Official Website)



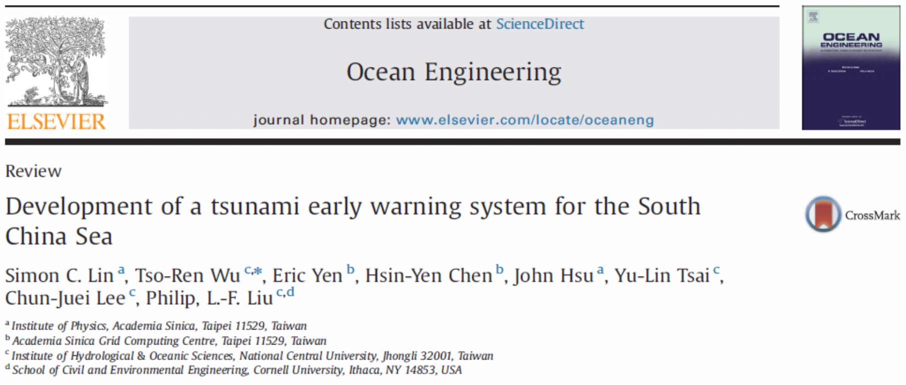


(2). High-speed Calculation

CWB COMCOT-Surge Model can finish 48 hrs forecast in 30 mins 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

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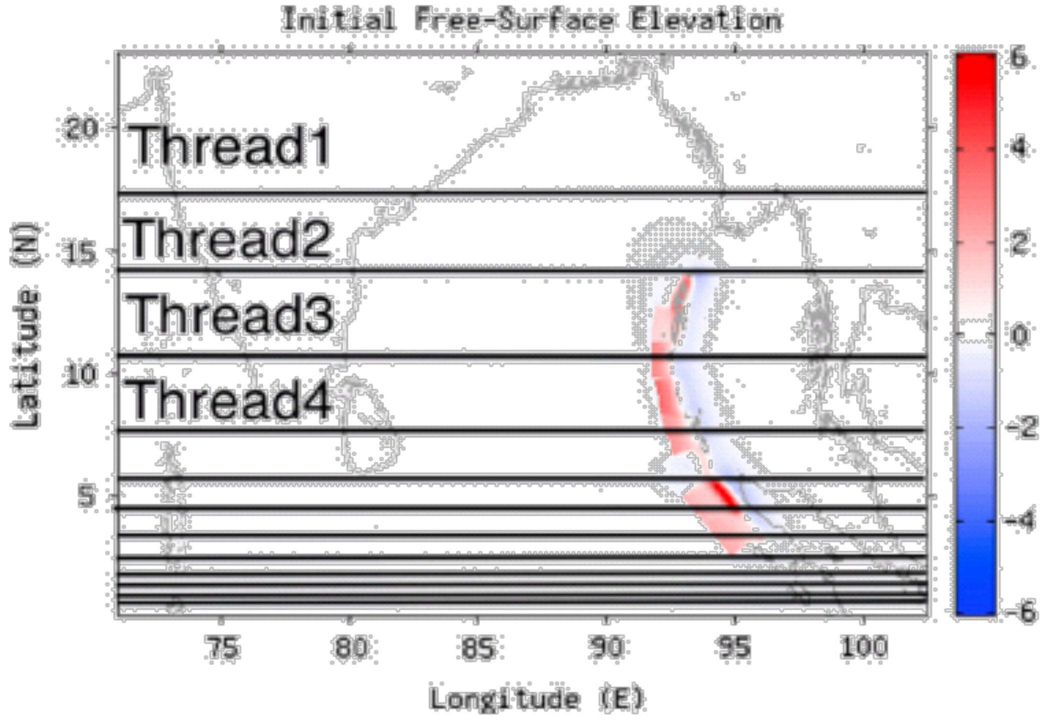
[b] Academia Sinica Grid Computing Centre, Taipei 11529, Taiwan
[c] Institute of Hydrological & Oceanic Sciences, National Central University, Jhongli 32001, Taiwan
[d] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

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



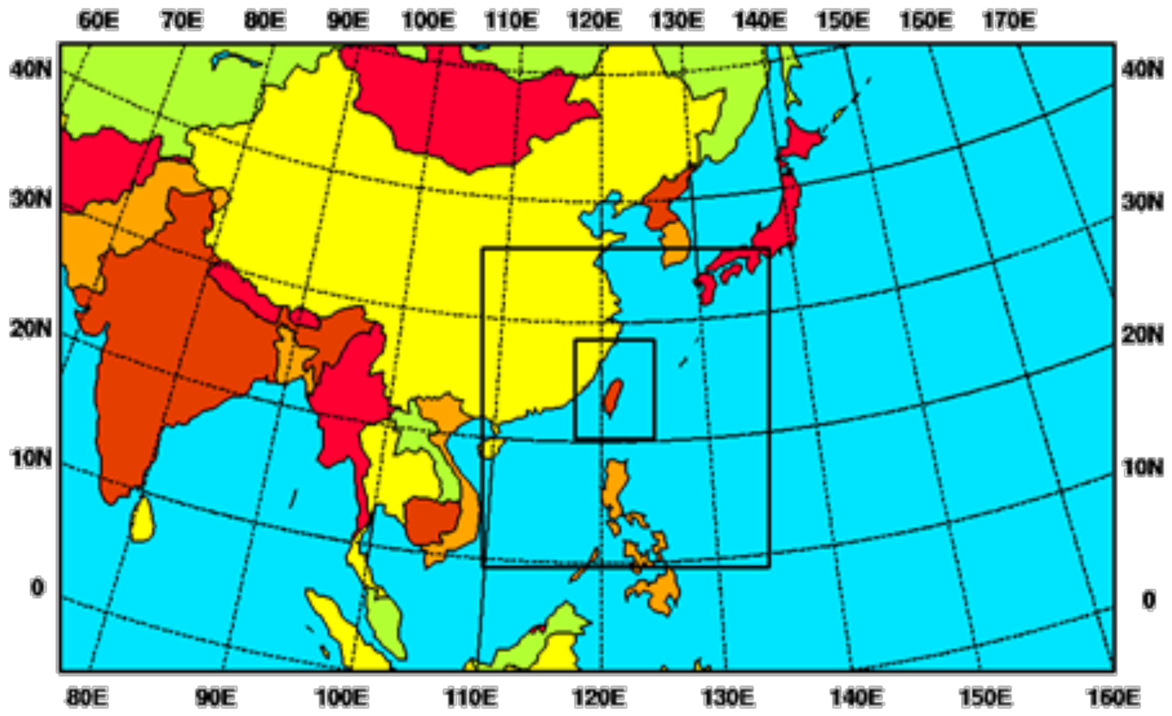
Dynamic resources sharing.

(3). Combine with the Atmospheric WRF/ TWRF Model

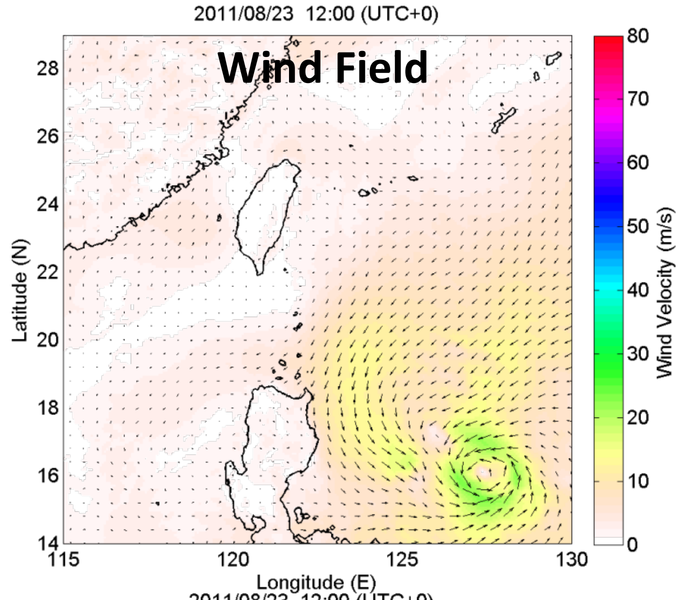
TWRF (Typhoon Weather Research and Forecasting Model)

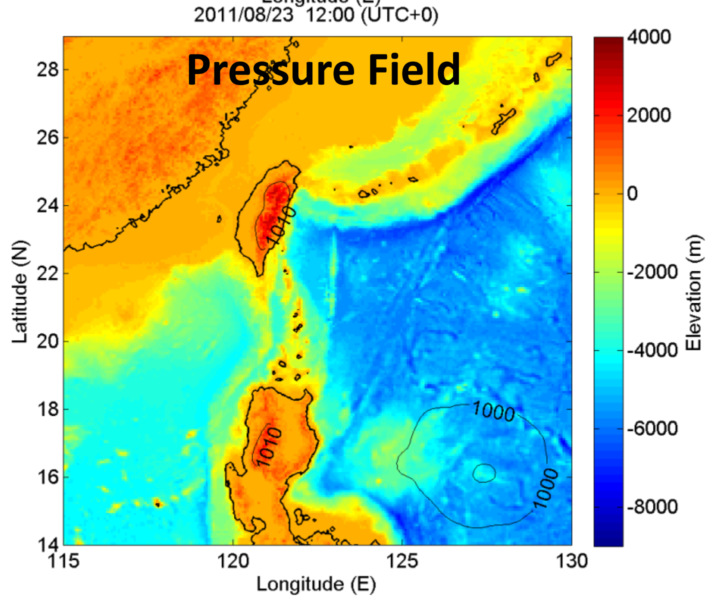
- TWRF model is an atmospheric model adopted for operational forecasts by Central Weather Bureau in Taiwan.

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



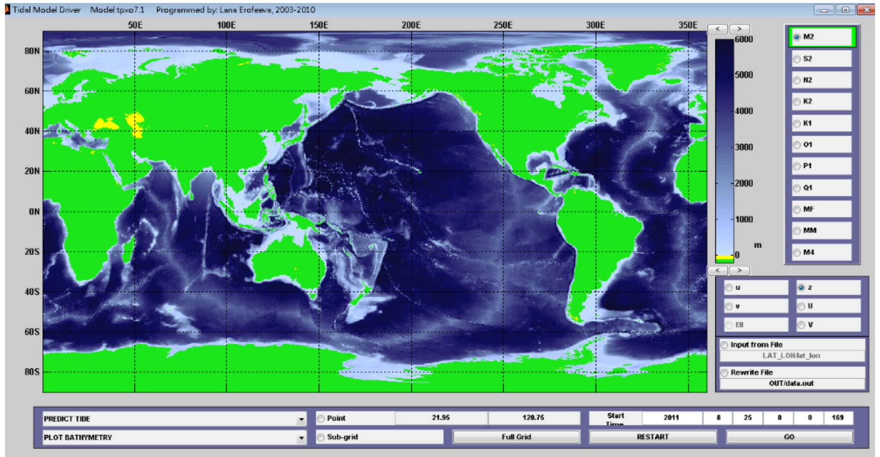
WRF Computational Domain (CWB)





(4). Combine with Global Tide TPXO Model

(USA OSU 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.

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 (3–8×10^{-9} s^{-1}, 210–310°) agree with those derived from the TPXO.2 model (2–5×10^{-9} s^{-1}, 250–300°), whereas harmonic constants of about (1–2×10^{-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.

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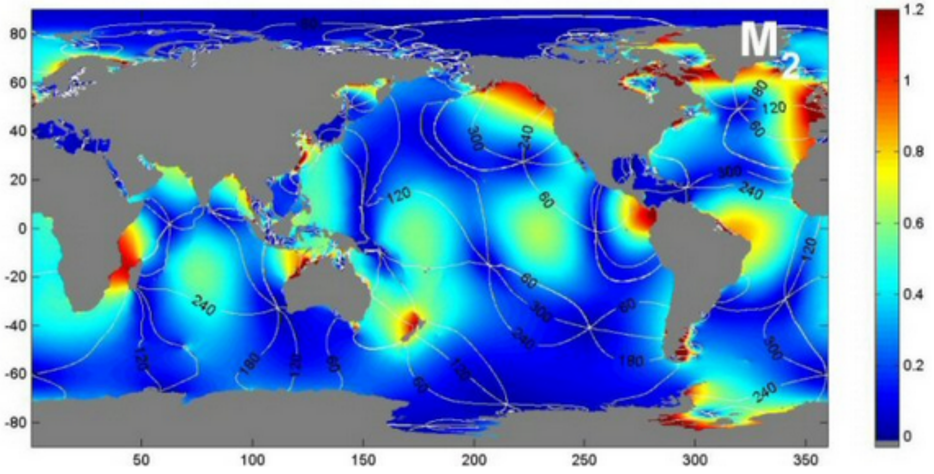
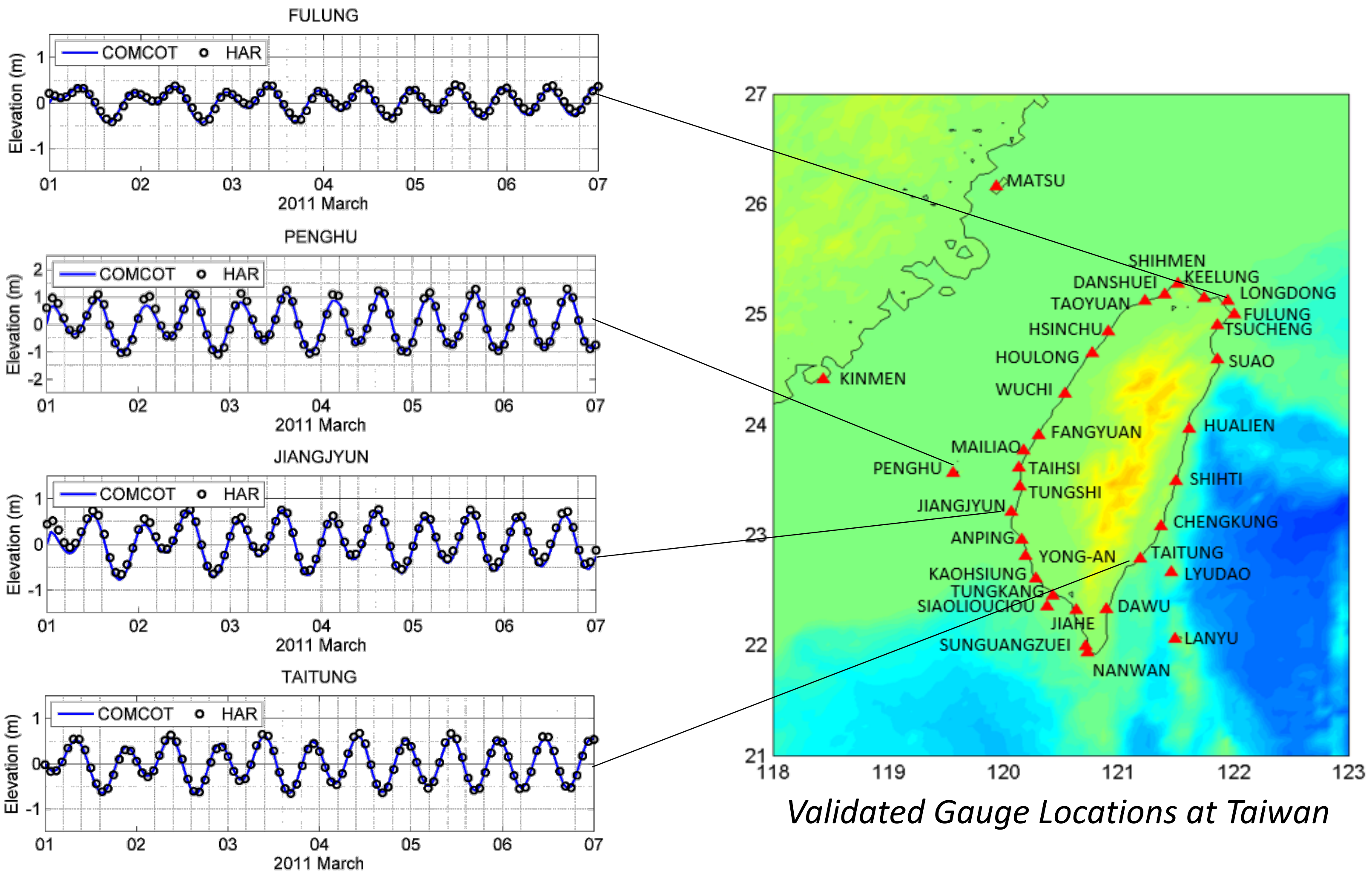


TPXO can provide tidal information, like M2.

(Dushaw et al., 1997)

(5). High-Accuracy Tide Simulation

The bias is smaller than 0.1 m and RMSE is smaller than 0.4 m.



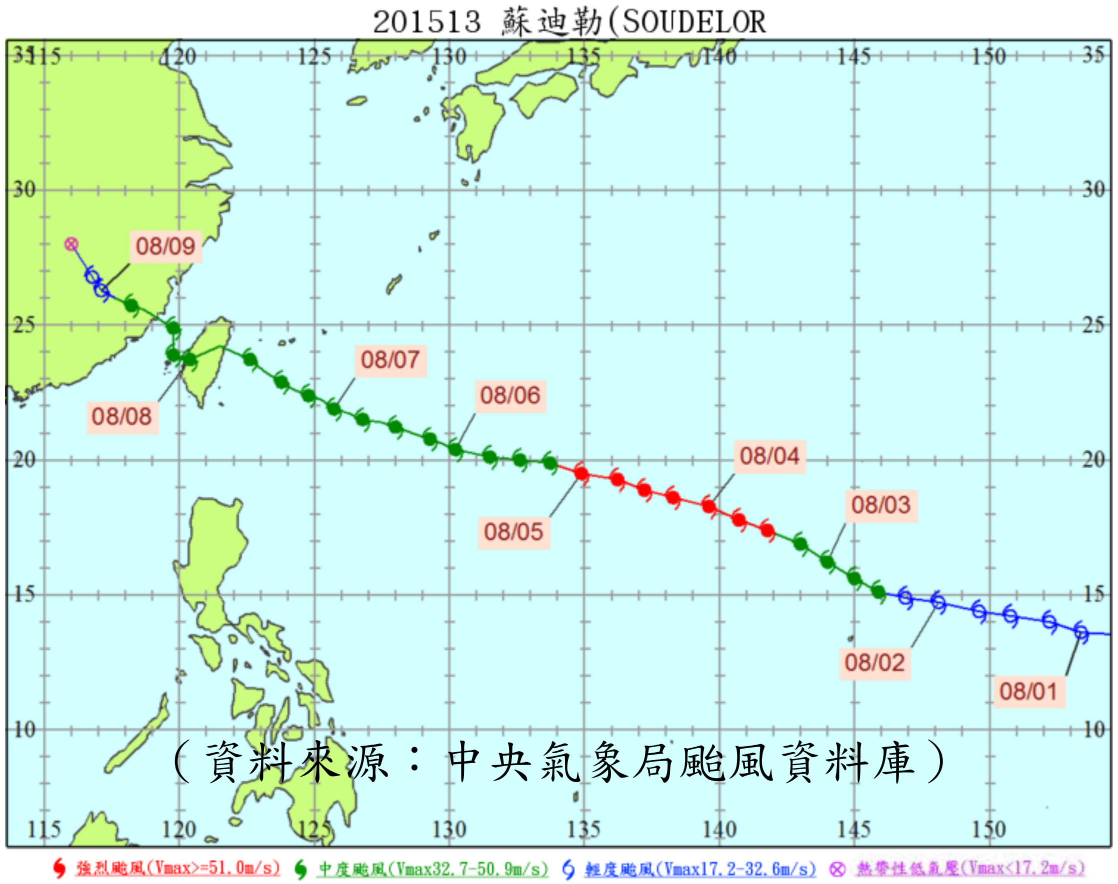
Validated Gauge Locations at Taiwan

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

(6). Model Validation of 2015 Typhoon Soudelor

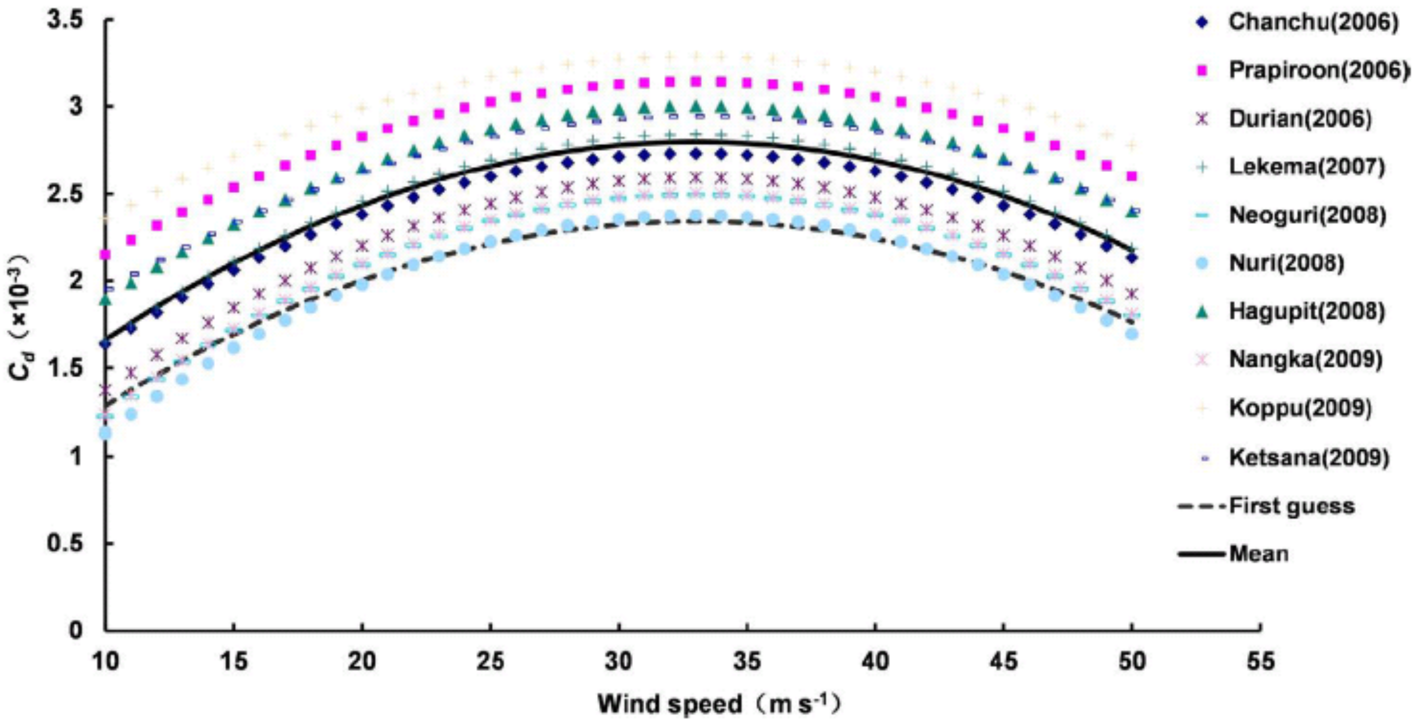
- Typhoon Soudelor was the strongest typhoon in Western North Pacific regions at 2015. According to the brief analysis, more than 4,000 thousands families lost their electricity during typhoon period and accumulative rainfall is more than 1,000 mm.
- Because of the destructive damages, economic loss 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)



Parabolic Drag Coefficient

$$C_d = -a\left(V_p - 33\right)^2 + c$$

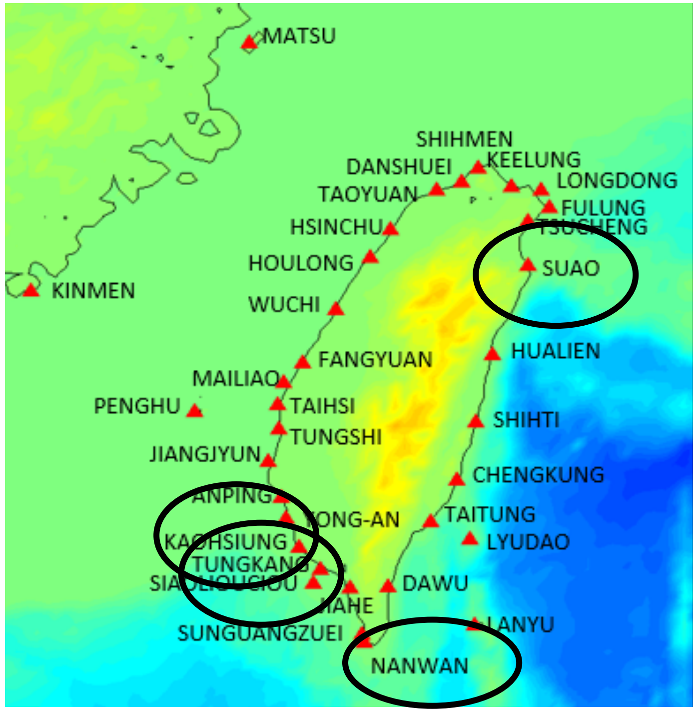


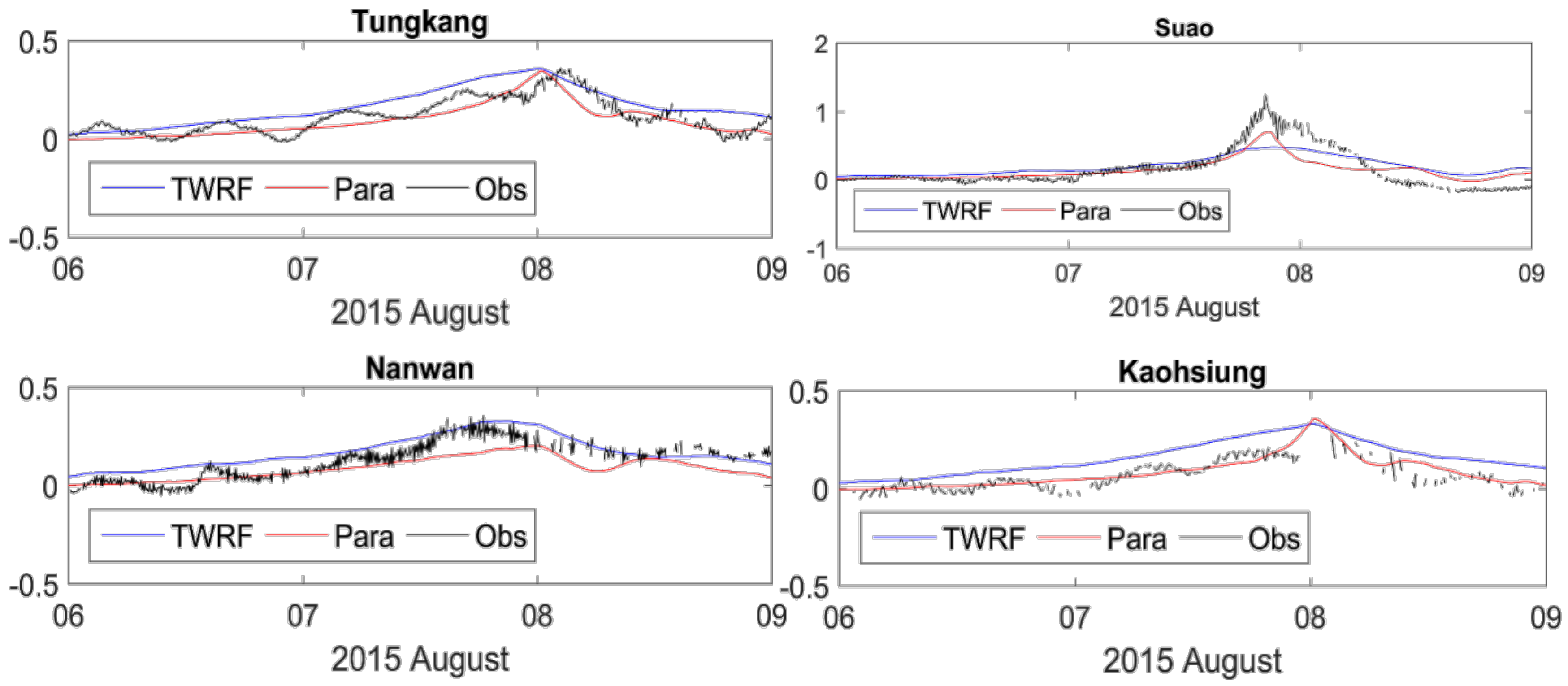
No.	Typhoon	*a*	*c*
1	Chanchu	0.00212	2.787
2	Prapiroon	0.00188	3.146
3	Durian	0.00231	2.593
4	Lekima	0.00226	2.839
5	Neoguri	0.00241	2.495
6	Nuri	0.00236	2.376
7	Hagupit	0.00210	3.003
8	Nangka	0.00240	2.503
9	Koppu	0.00176	3.287
10	Ketsana	0.00188	2.945
	Mean	0.00215	2.797

(Peng and Li, 2015, Nature)

Comparison with Observed Data

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

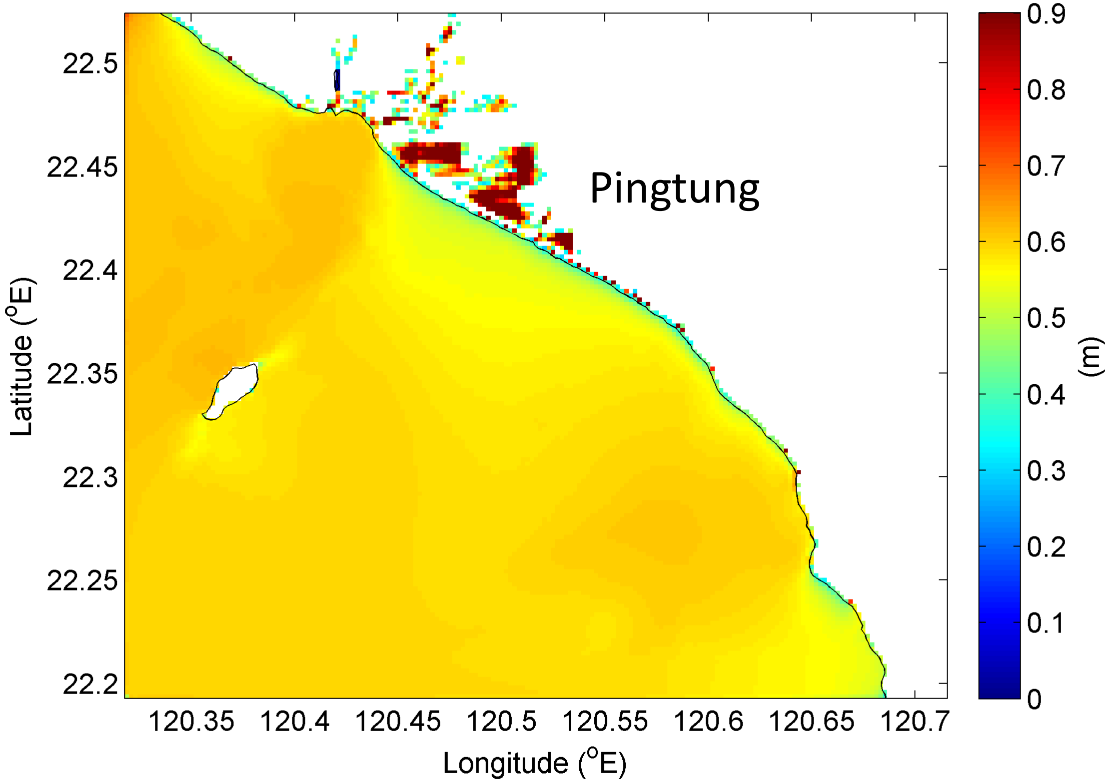




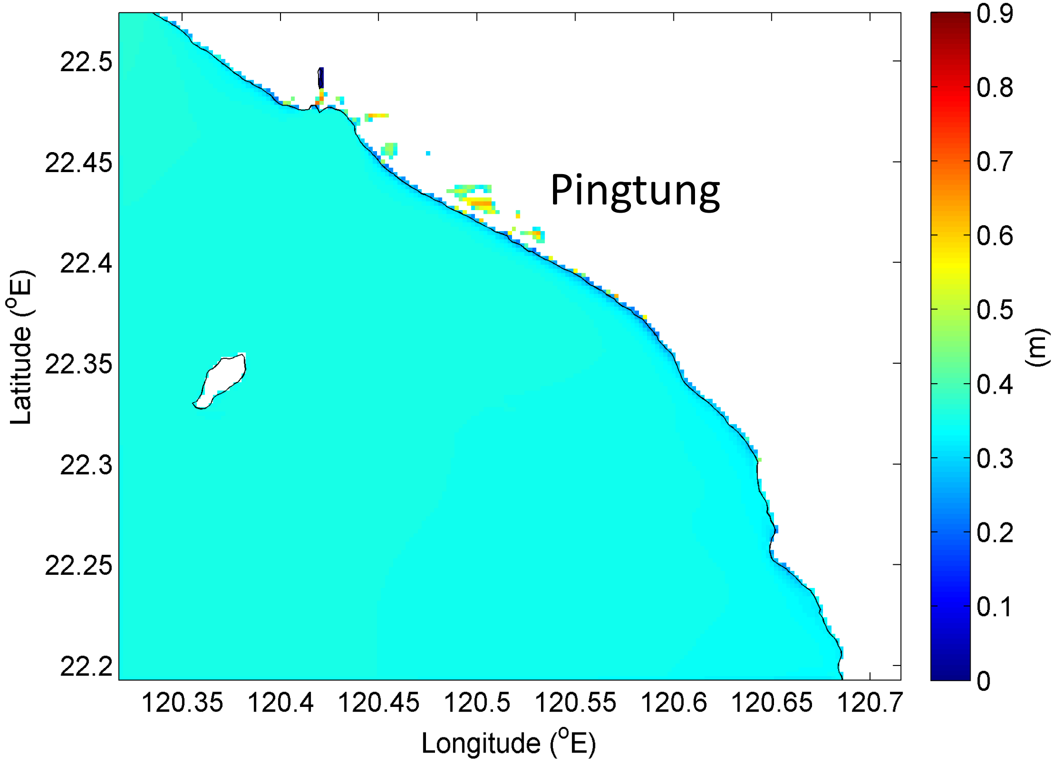
The tide observed data are provided by our CWB in Taiwan.

Coastal Inundation Calculation

Storm Tides (Storm Surge + Tide)

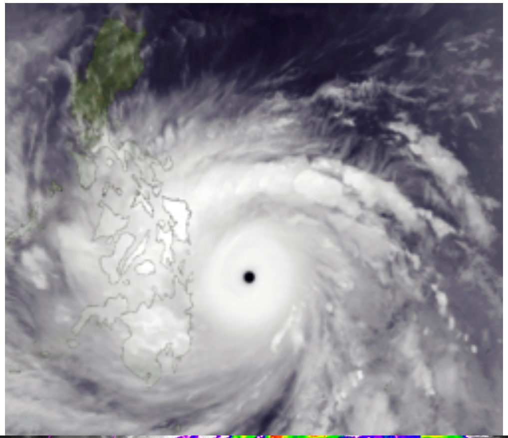


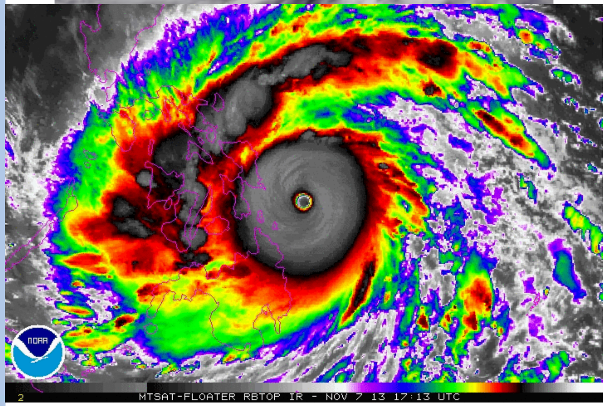
Pure Tide



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.

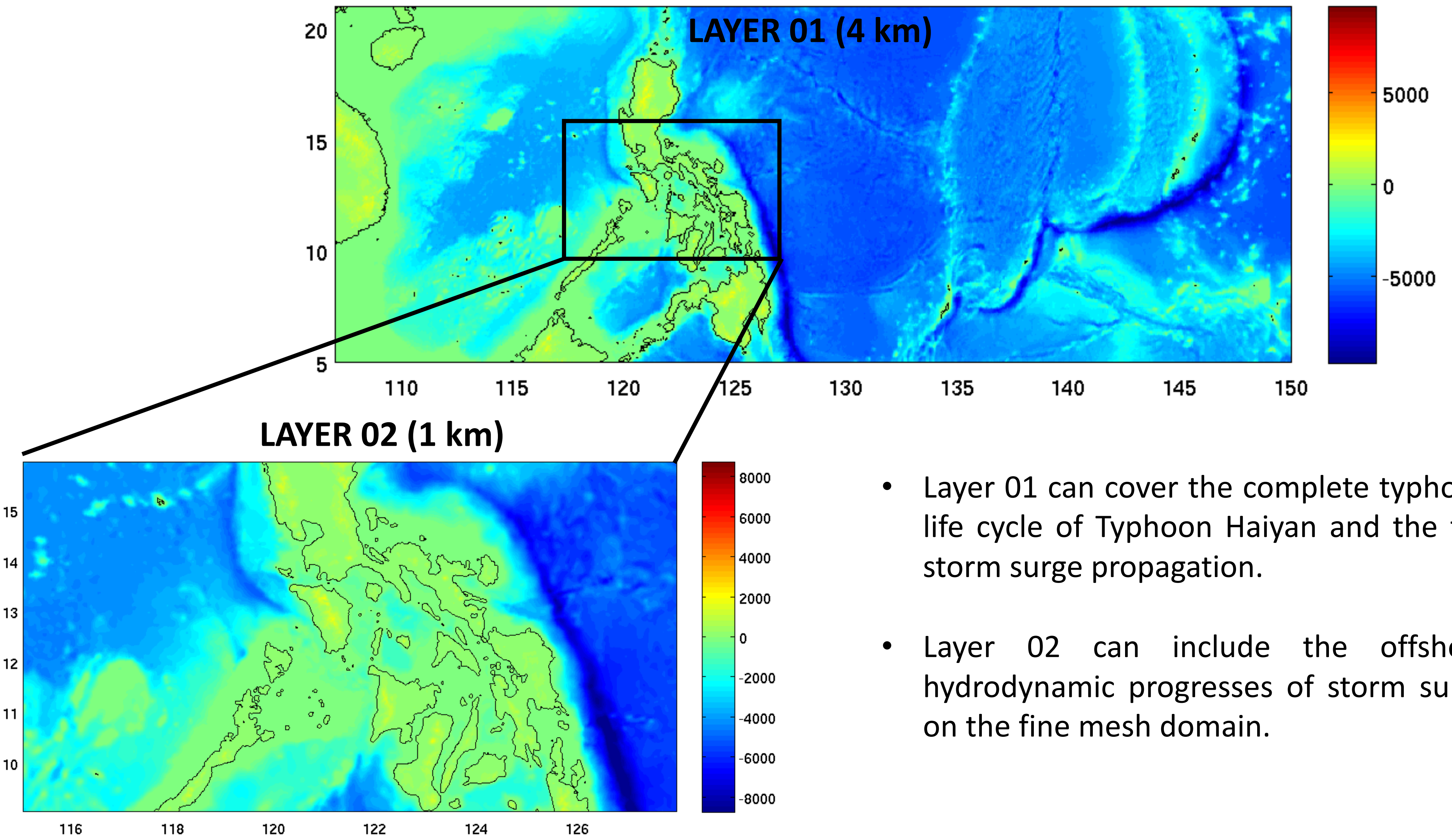
The Case Study of 2013 Typhoon Haiyan





Source: Hong Kong Observatory

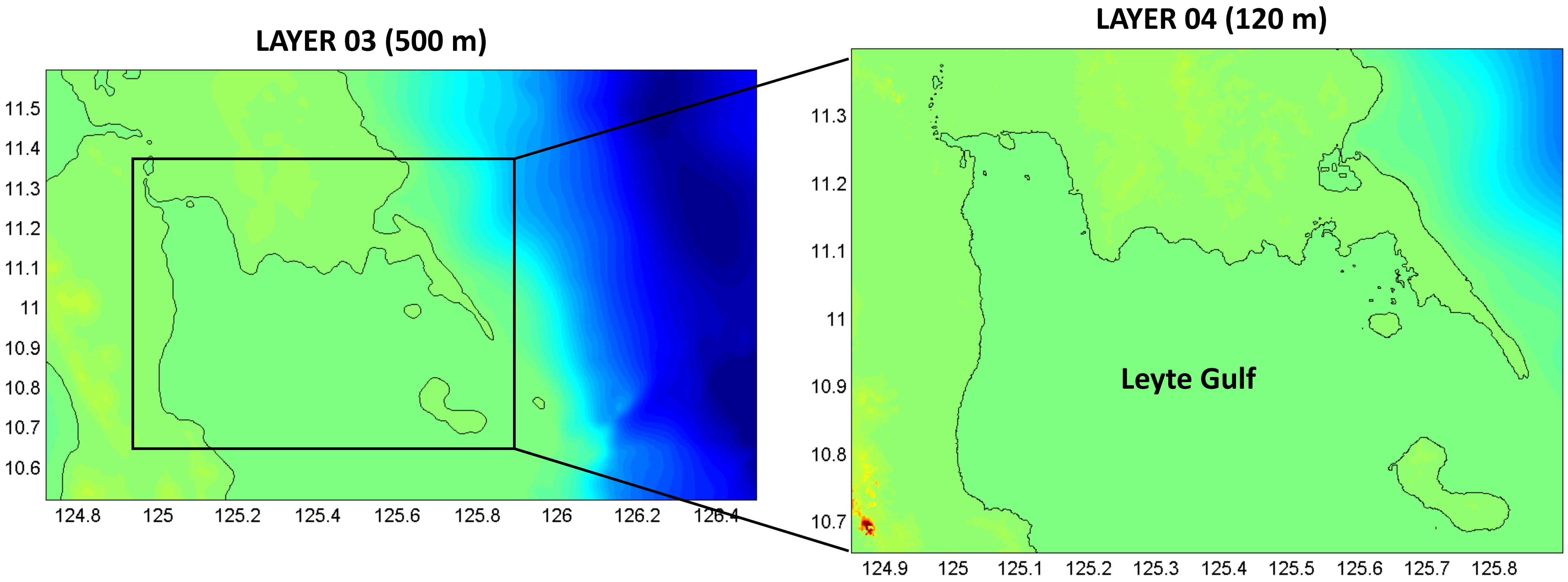
Nested Computational Domain



- 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.

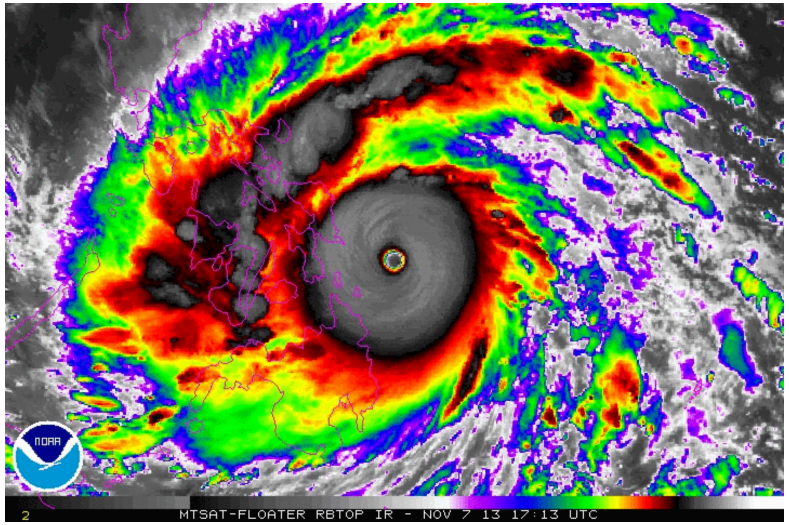
Near-shore Computational Domain

Layer 03 (500 m)/ Layer 04 (120 m)



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

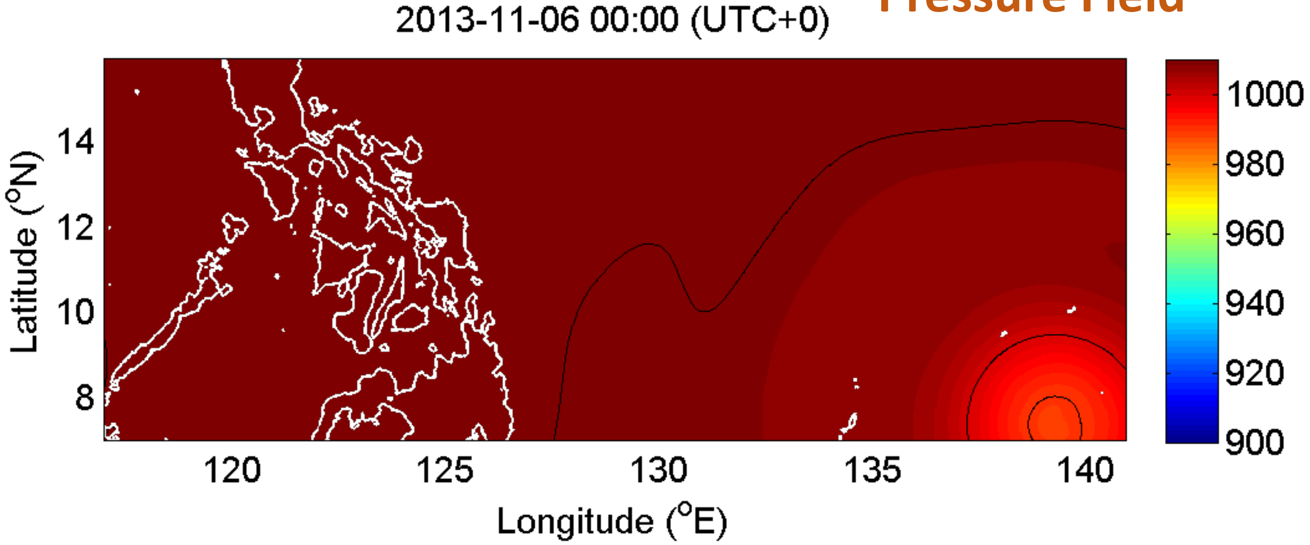
Combine with the Atmospheric WRF Model



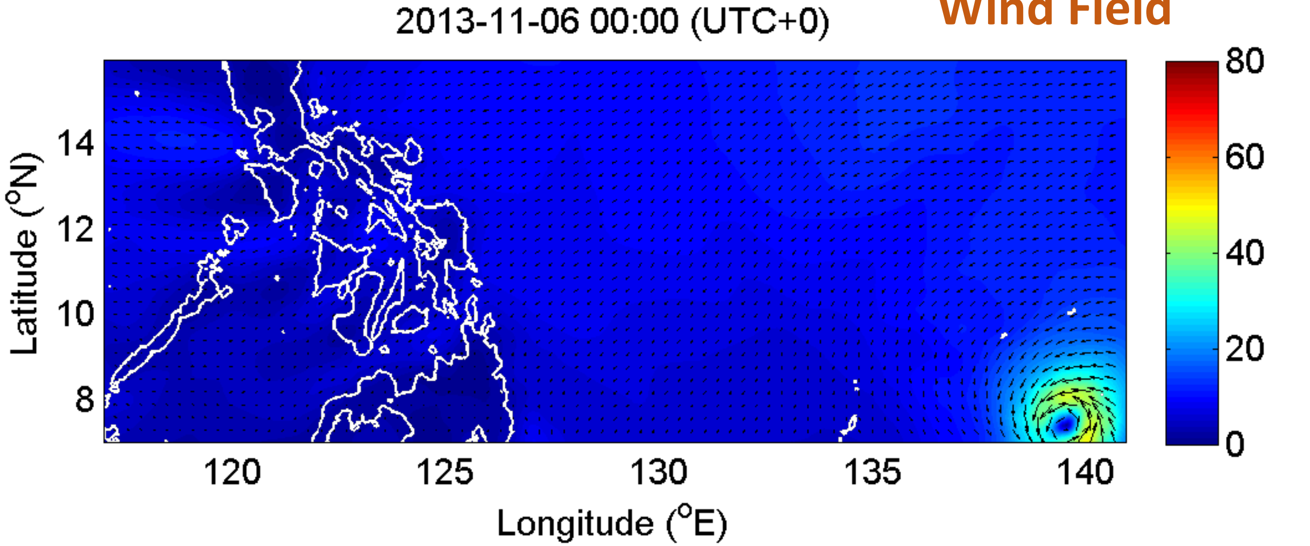
- *Asymmetric effect*
- *Topographic effect*
- *Hydrodynamic Pressure*

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

Pressure Field

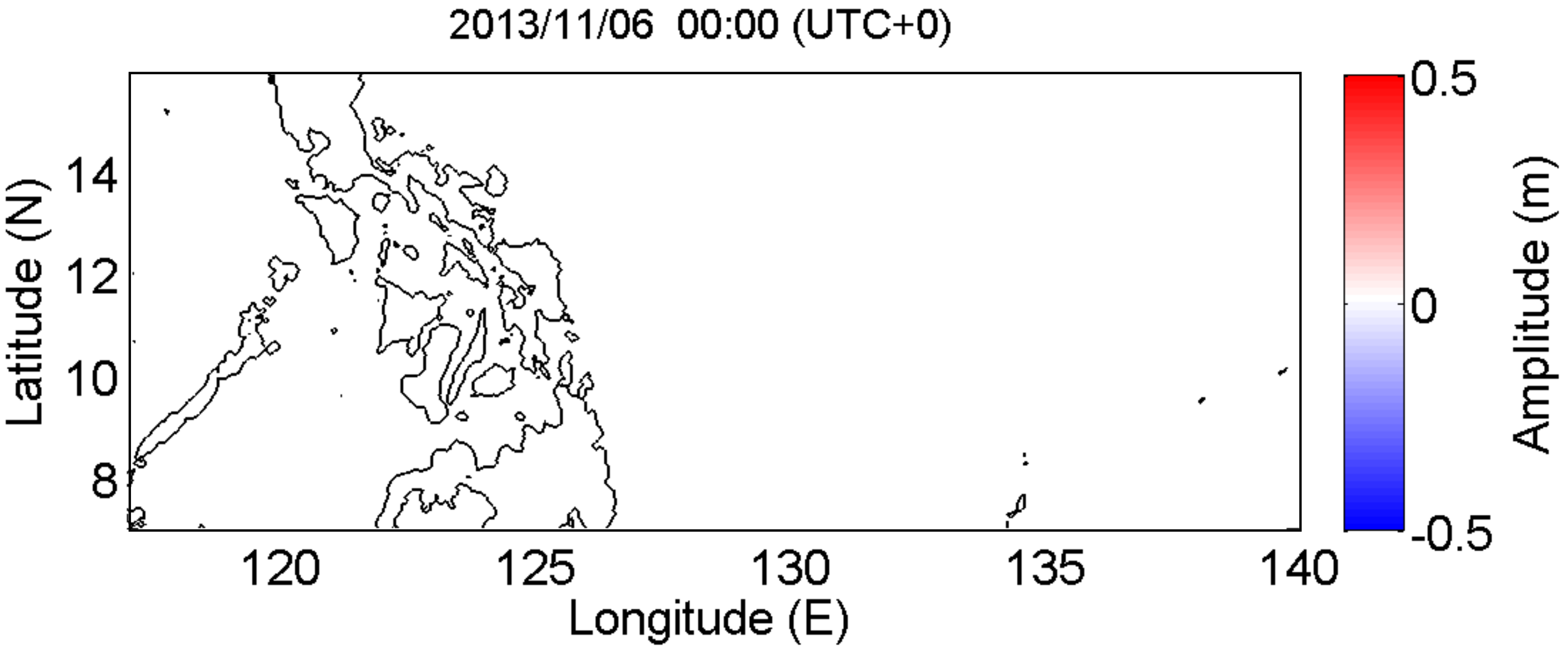


Wind Field



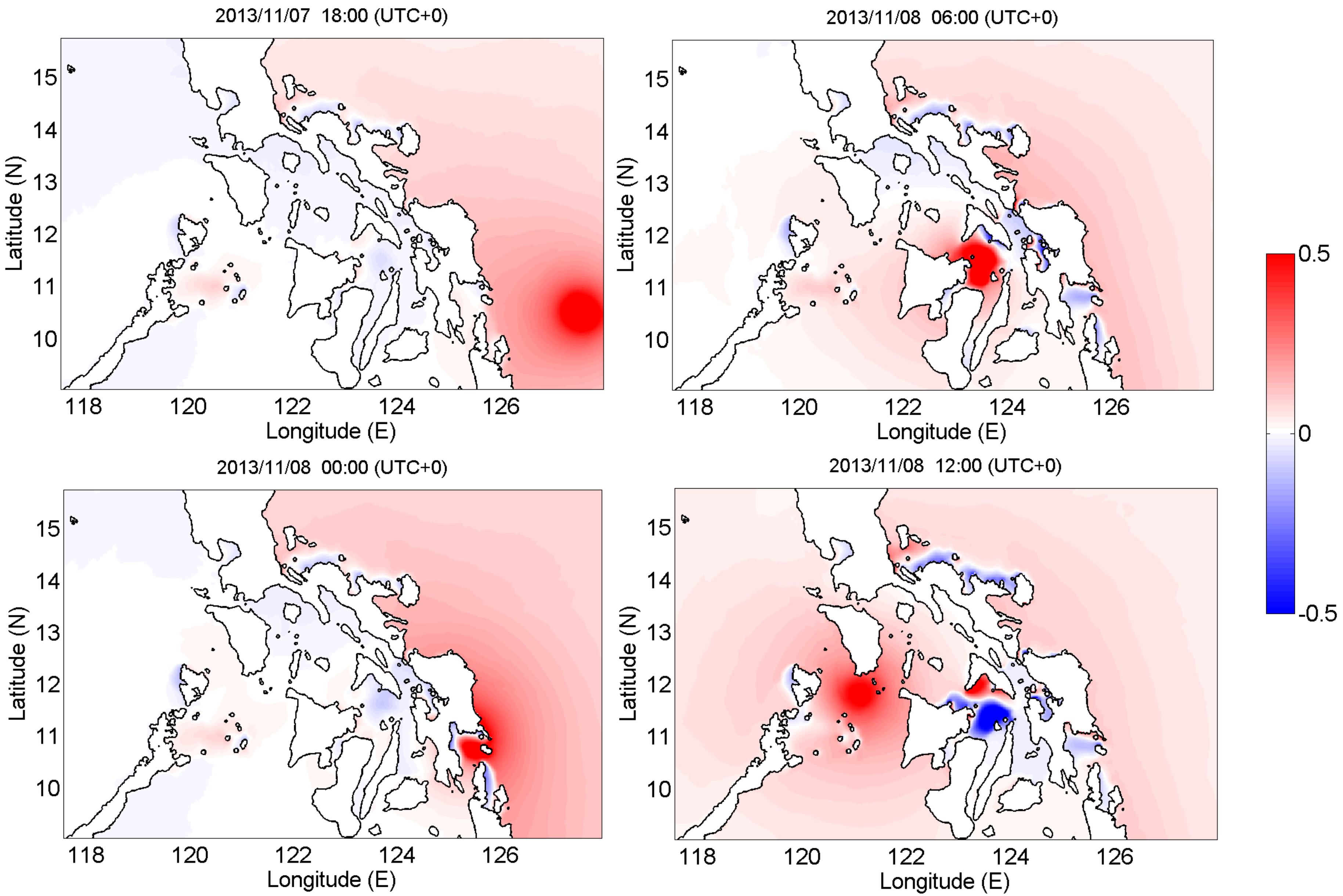
Storm Surges Induced by Typhoon Haiyan

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

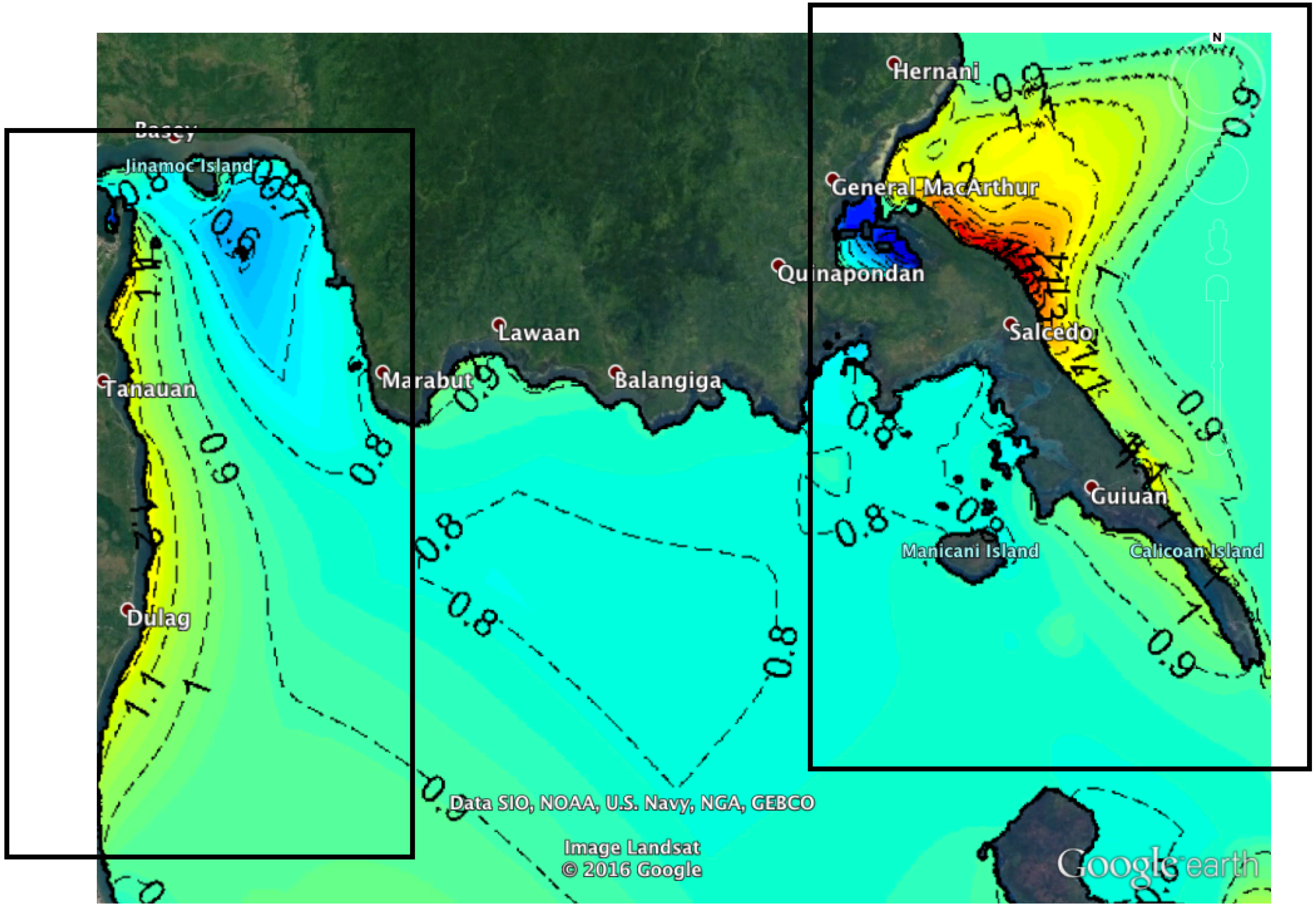


Large computational domain to cover the complete storm surge propagation induced by Typhoon Haiyan with Coriolis effect.

Snapshots of Storm Surges in the Philippines

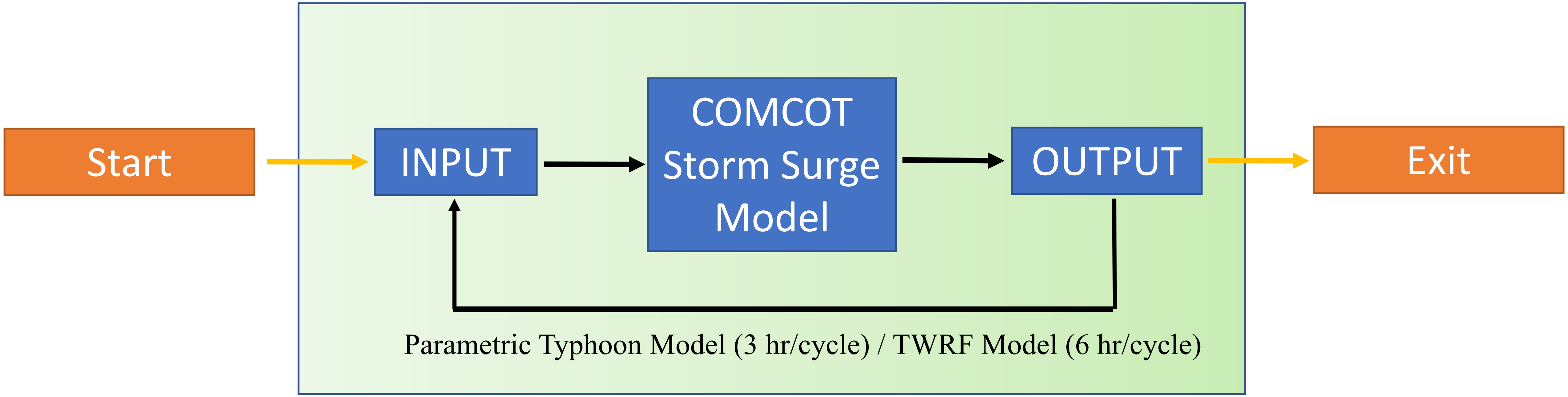


Maximum Simulated Storm Tides at Leyte Gulf



Storm Surge Operational System

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



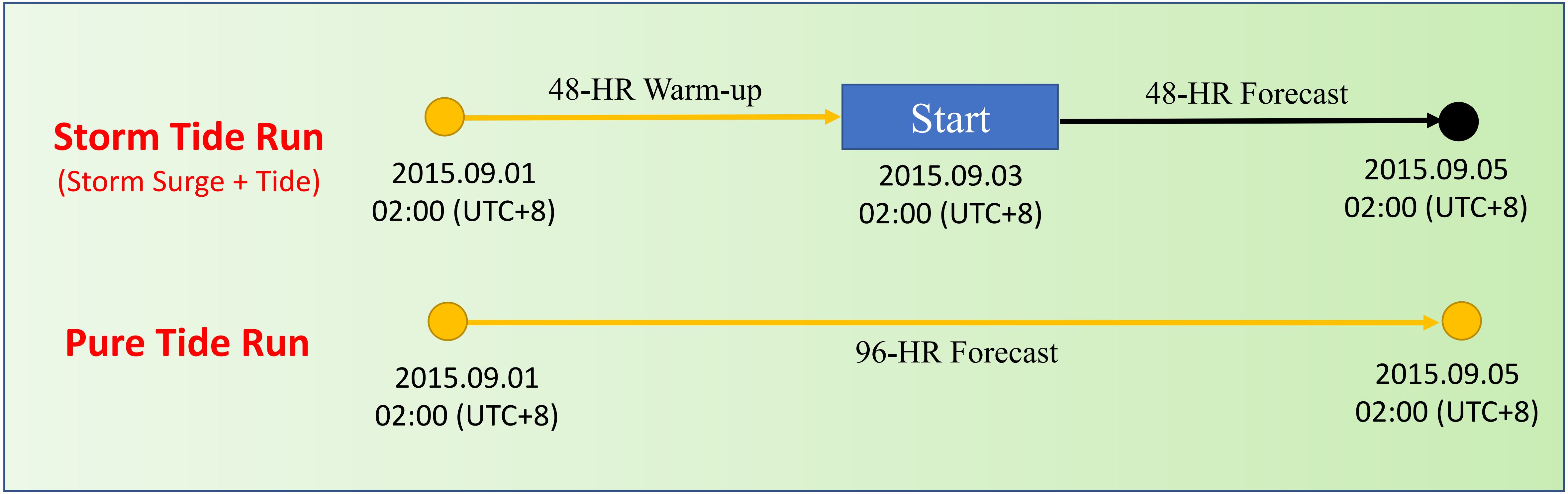
INPUT

- Meteorological Force: Parametric Typhoon Model or TWRF 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.

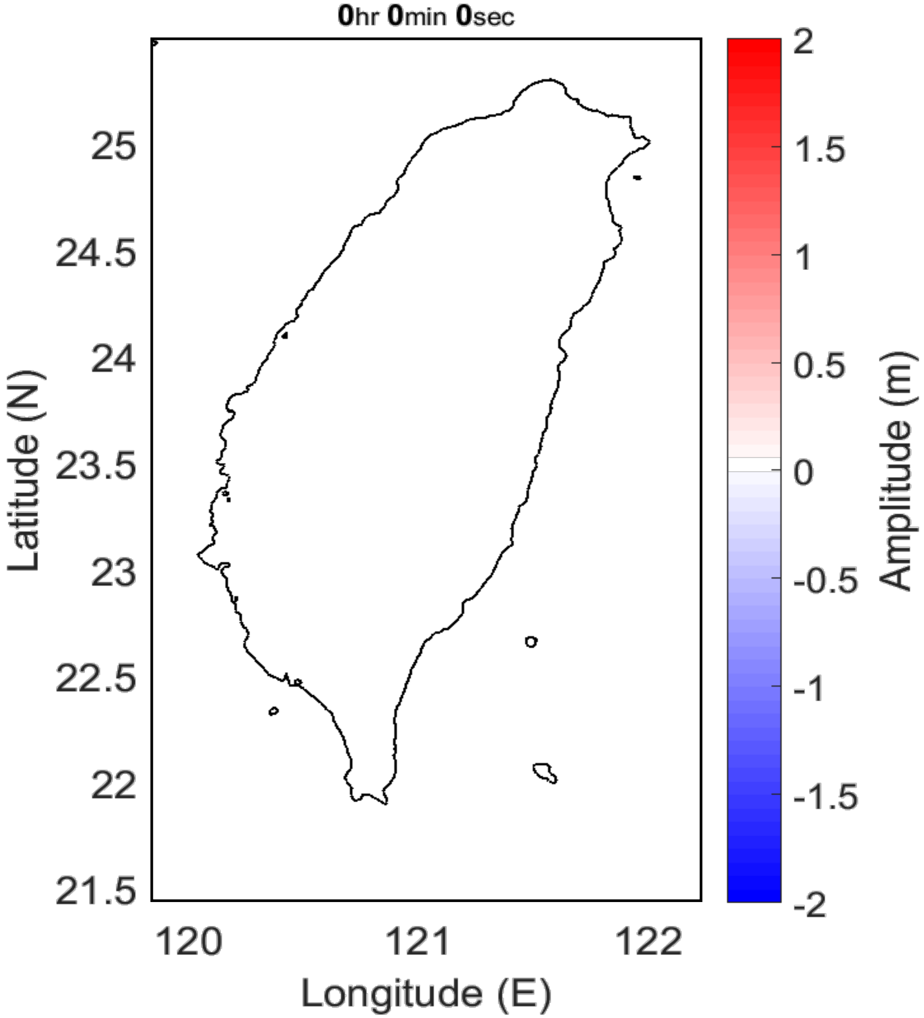
Comparison with Other Operational Storm Surge Model

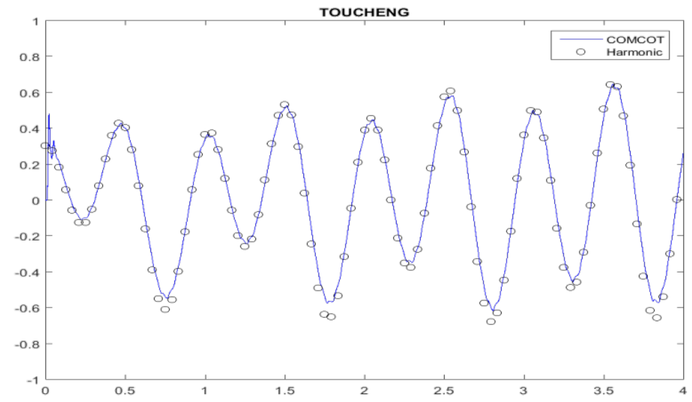
Model	Country	Resolution	Coordinate	Grid System	Inundation	Nonlinear Tidal Effect
SLOSH	USA	3 km	Polar	Structured	Yes	No
ADCIRC	USA/China	1 km	Spherical	Unstructured	Yes	Yes
JMA	Japan	2 km	Cartesian	Structured	No	No
POM	Korea	10 km	Cartesian	Sigma Grid	No	Yes
COMCOT Storm Surge Model	Taiwan	1 km	Spherical/ Cartesian	Nested-Grid System	Yes	Yes

- Solve **spherical nonlinear** shallow water equation directly with **Coriolis effect**.
- Cover complete storm surge propagation from open oceans to coastal regions.
- Calculate **high-resolution storm surge inundation**.
- **Tide warm-up** is stable and low-time consuming.
- The resolution in coastal regions can be promoted easily and be separately calculated in **nested-grid scheme**.
- Bathymetry and elevation data are easily to be input.
- The resolution can be modified easily.

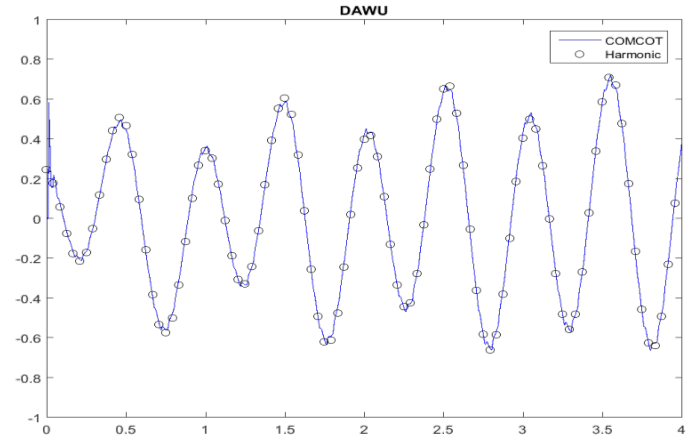
Tide Validation of COMCOT-SURGE Model

(2016.09.11 00:00 – 2016.09.15 00:00)

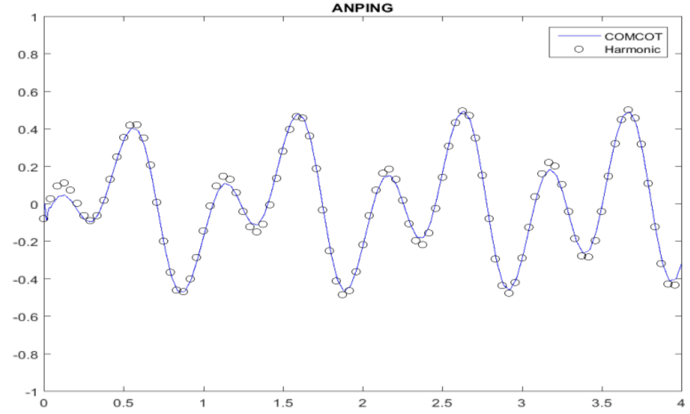




Toucheng
頭城



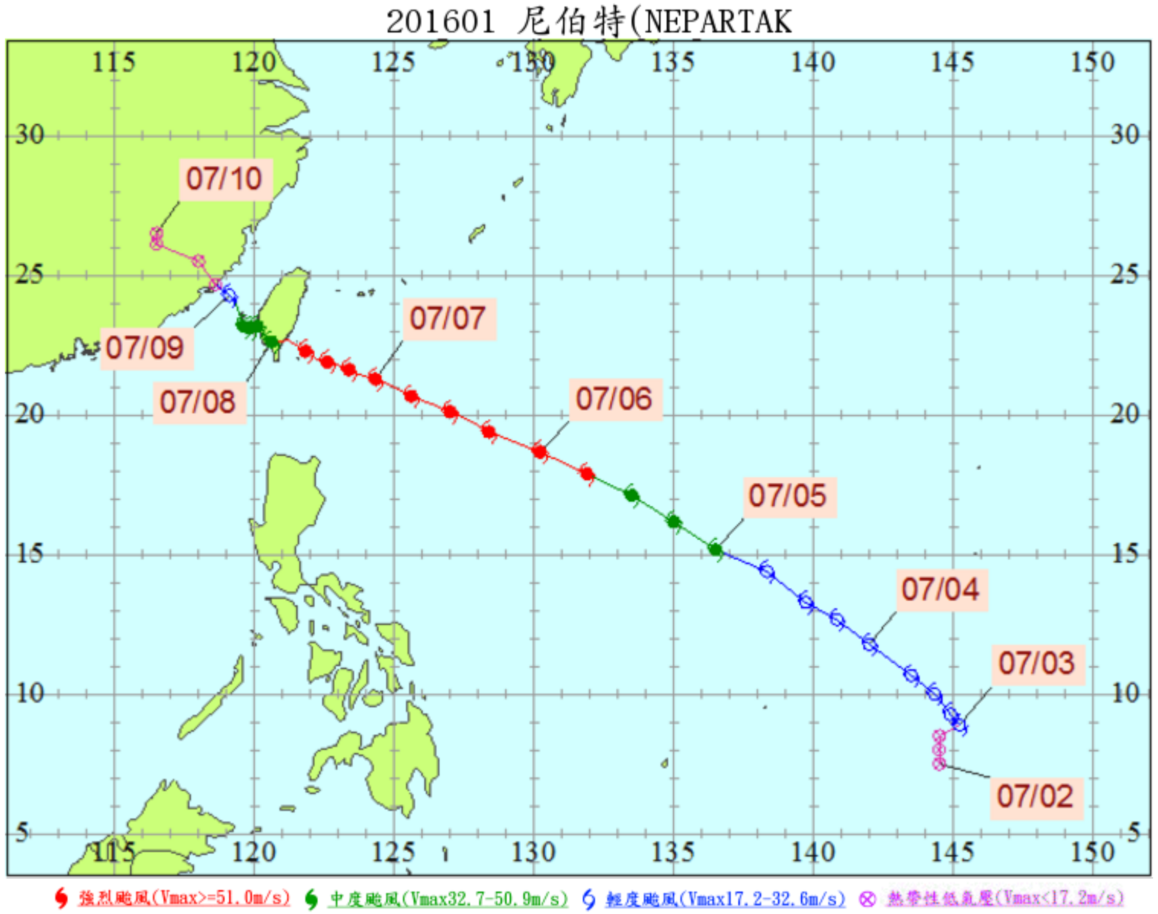
Dawu
大武



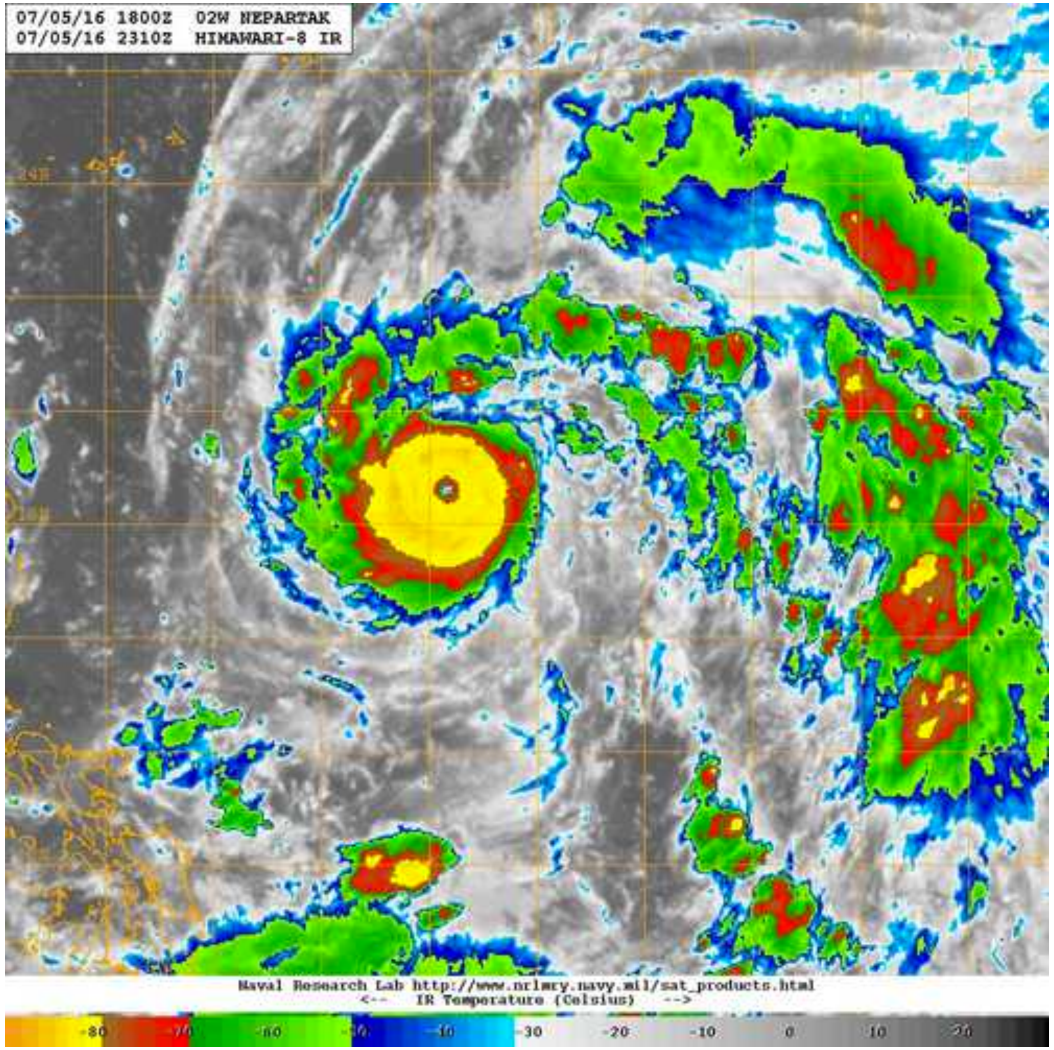
Anping
安平

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.

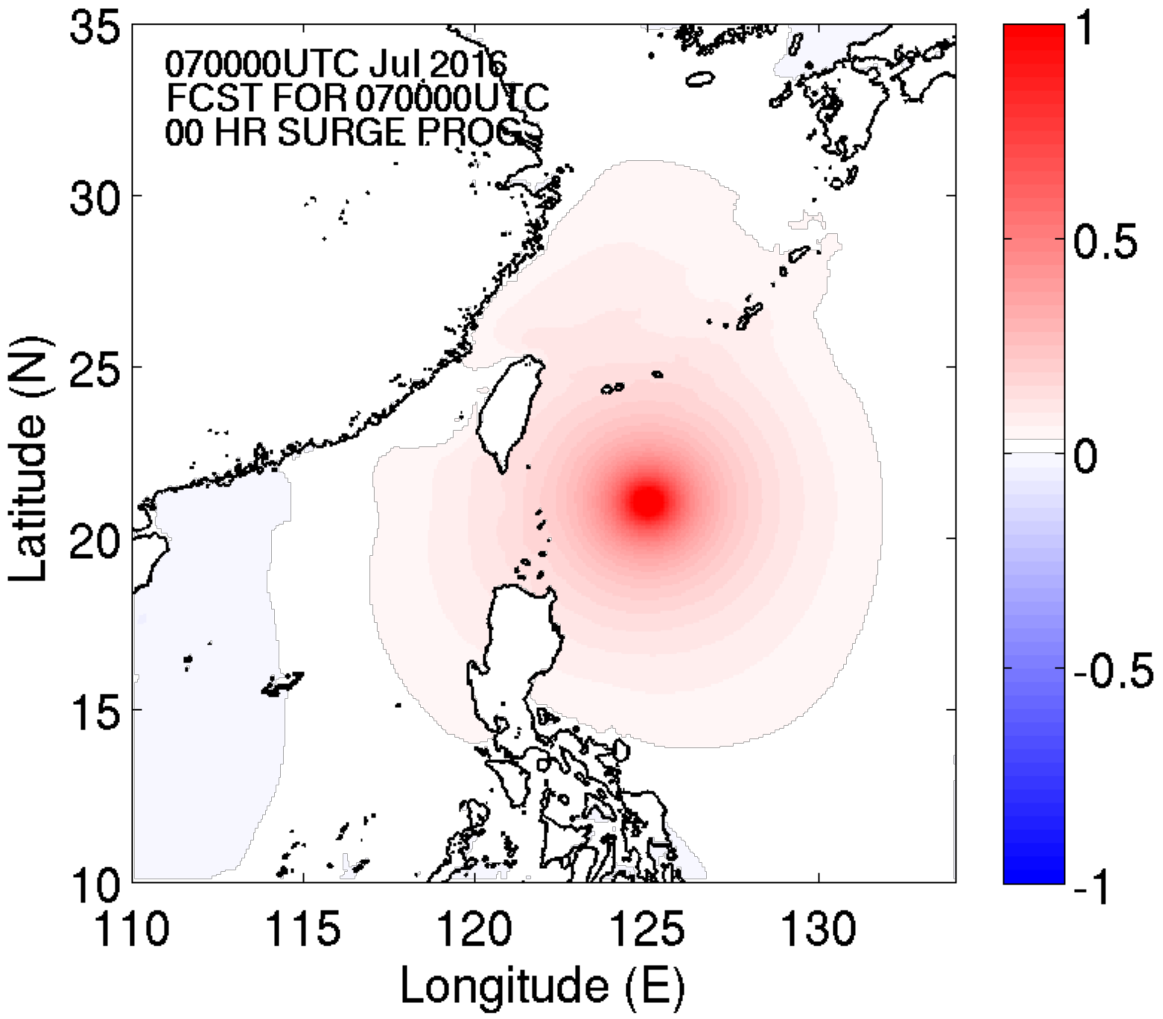


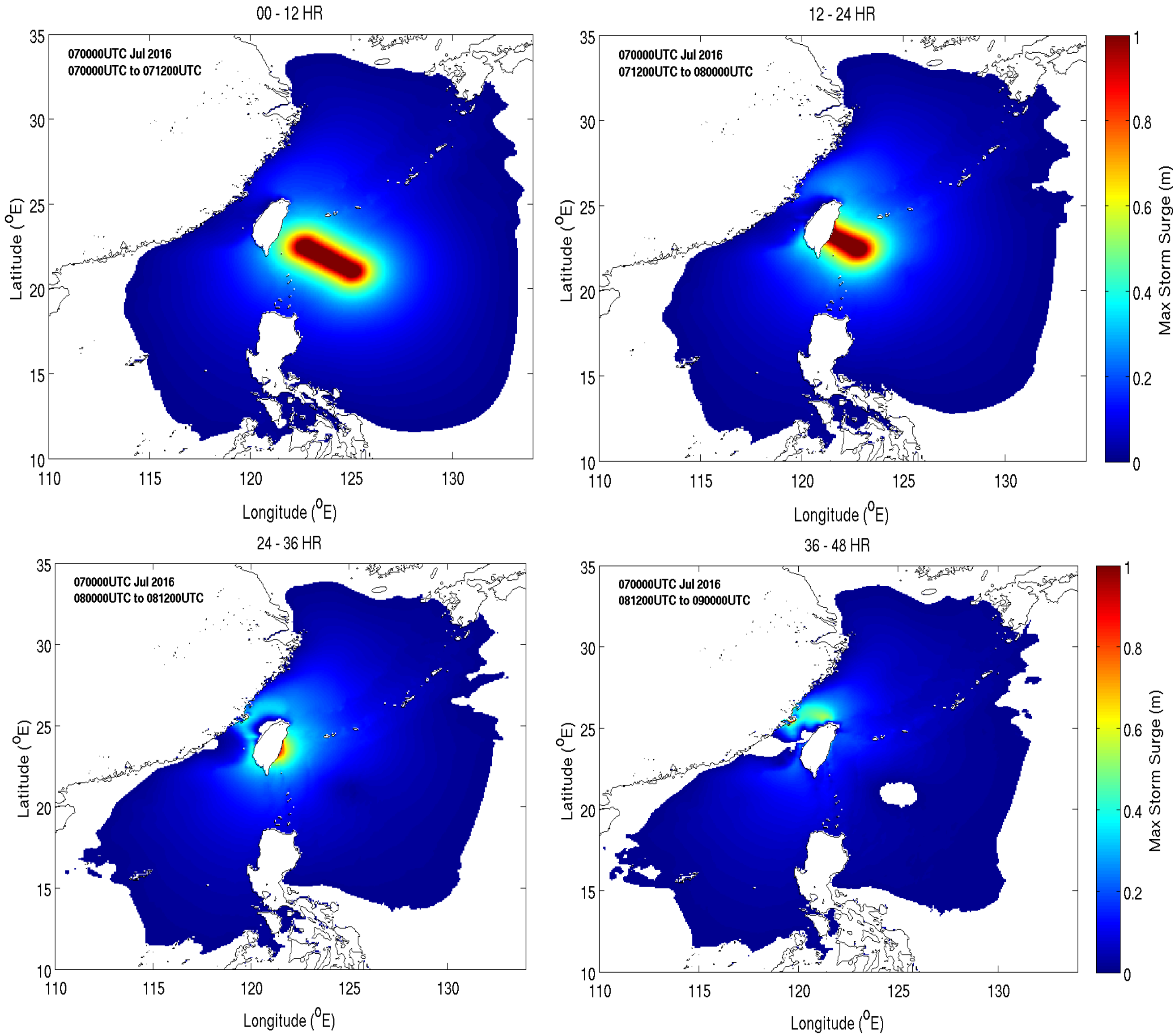
The track of Typhoon Nepartak (CWB, Taiwan)



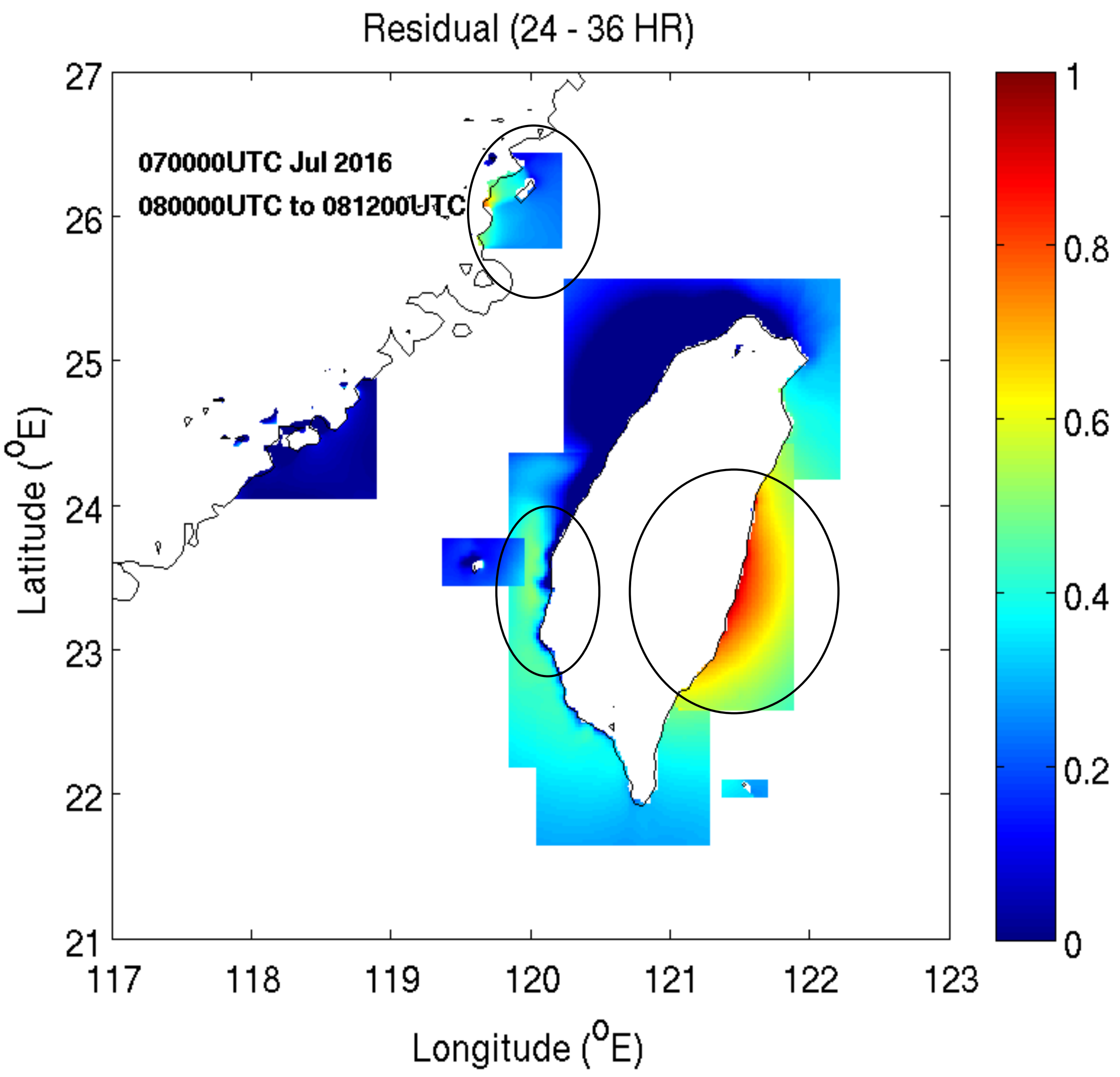
U.S Naval Research Laboratory

Storm Surges Induced by 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)

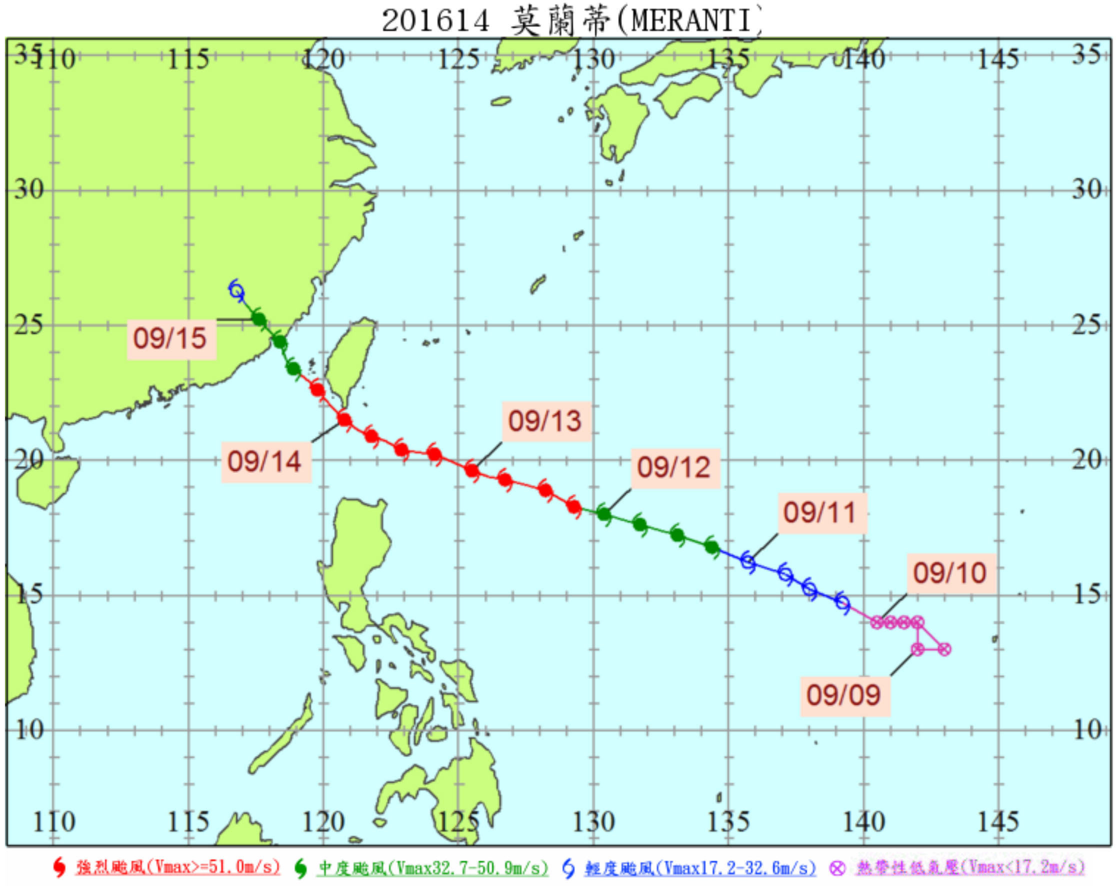
People live in these areas need to pay attention to the storm surge inundation.

Severe Typhoon Meranti in 2016

Typhoon Meranti was one of the most intense tropical cyclones on record. Impacting the Batanes in the Philippines, Taiwan, as well as Fujian, China in September 2016.

Best-track parameters of Typhoon Meranti

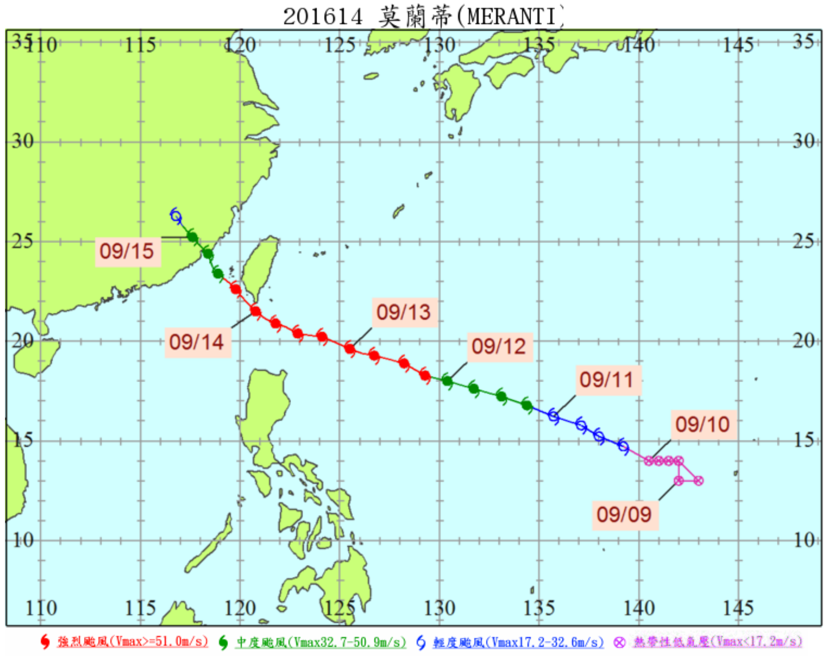
年	月	日	時	中心位置 (經/緯)		中心氣壓 (Pa)	七級風半徑 (km)	近中心最大風速 (m/s)
2016	9	12	00	130.4	18.0	940	180	45
2016	9	12	06	129.3	18.3	925	200	51
2016	9	12	12	128.2	18.9	910	200	55
2016	9	12	18	126.7	19.3	905	200	58
2016	9	13	00	125.5	19.6	905	200	58
2016	9	13	06	124.1	20.2	905	200	58
2016	9	13	12	122.9	20.4	**900**	220	60
2016	9	13	18	121.8	20.9	905	220	58
2016	9	14	00	120.8	21.5	905	220	58
2016	9	14	06	119.8	22.6	925	200	51
2016	9	14	12	118.9	23.4	930	200	48
2016	9	14	18	118.4	24.4	950	180	40
2016	9	15	00	117.6	25.2	970	150	33



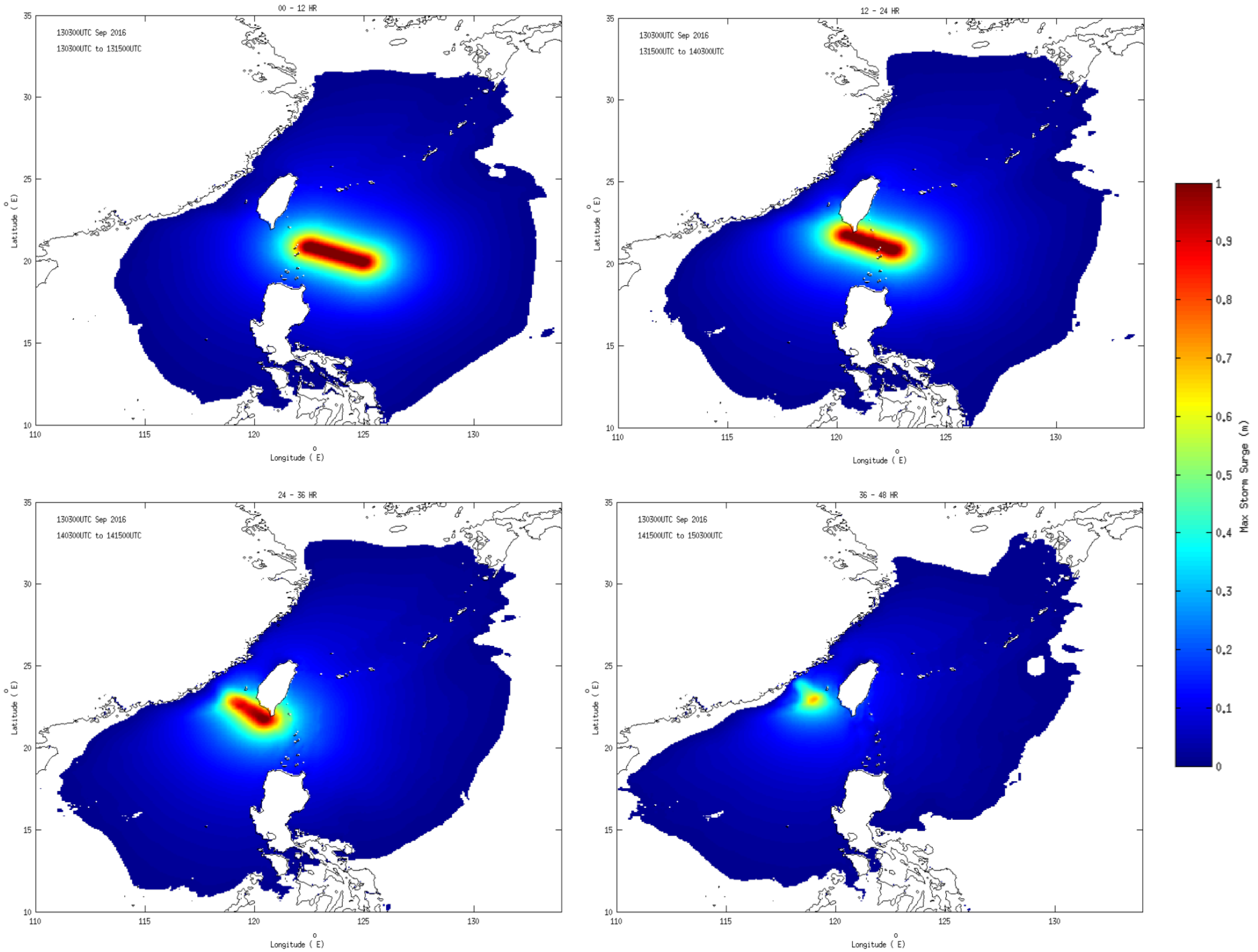
莫蘭蒂路徑圖

Forecast Product (1)
Maximum Storm Surge

2016年莫蘭蒂颱風
颱風警報單時間：2016031308

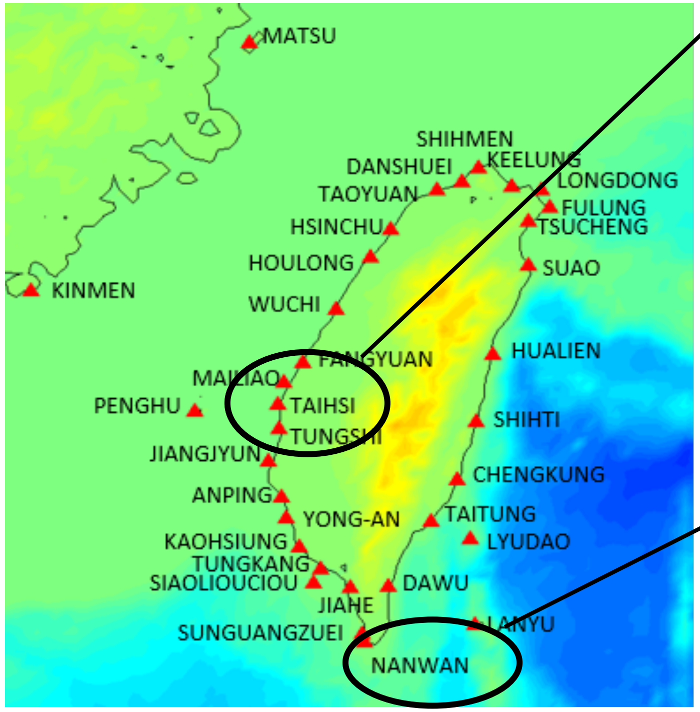


(颱風資料庫提供)

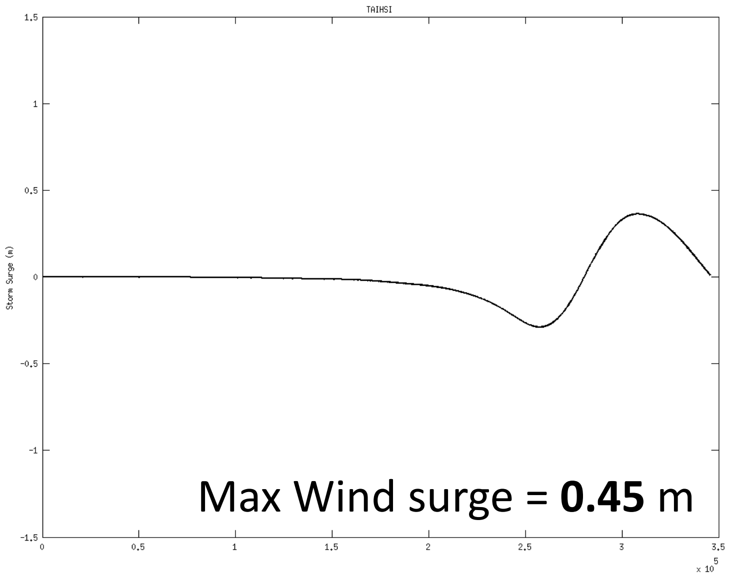


Contribution of Wind Shear Stress and Pressure Gradient

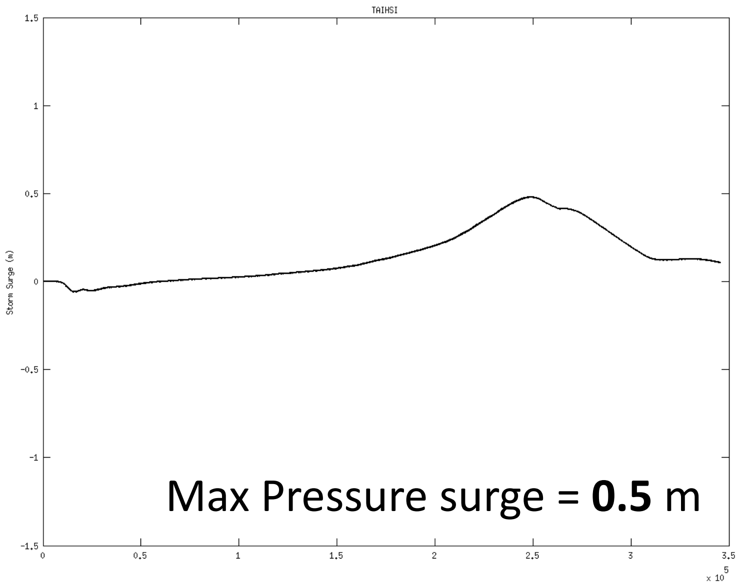
2016 Typhoon Meranti



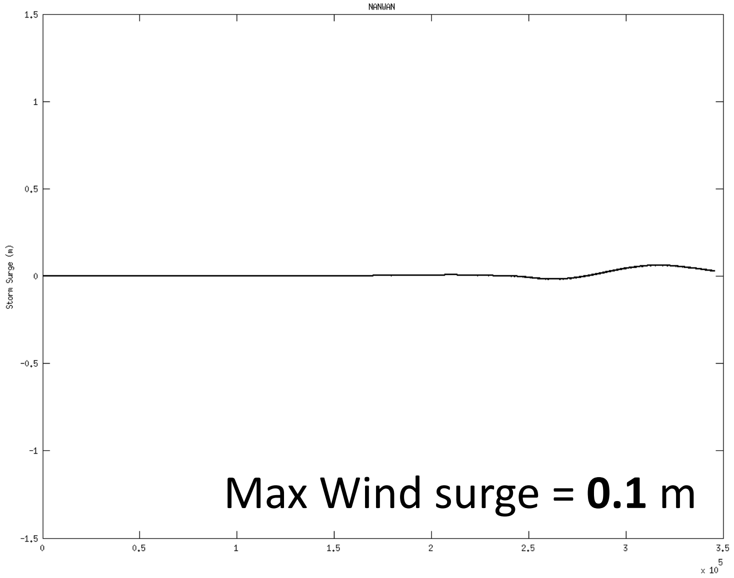
Wind Shear Stress (Taisi)



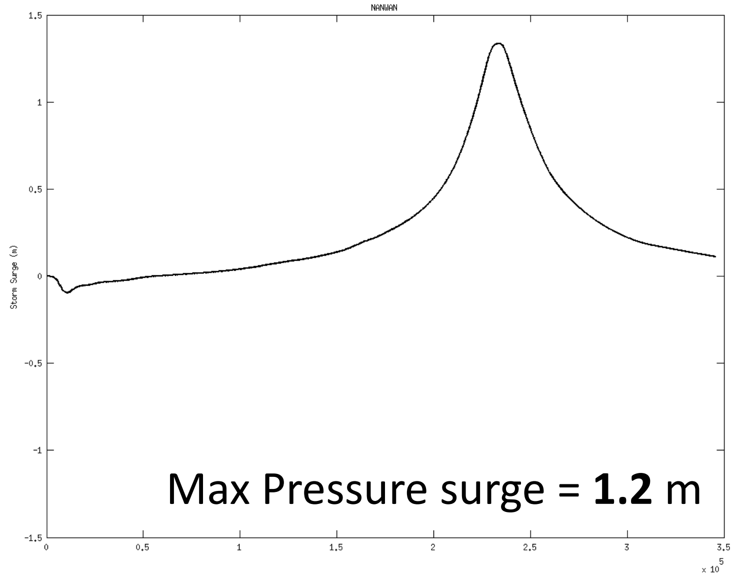
Pressure Gradient (Taisi)



Wind Shear Stress (Nanwan)

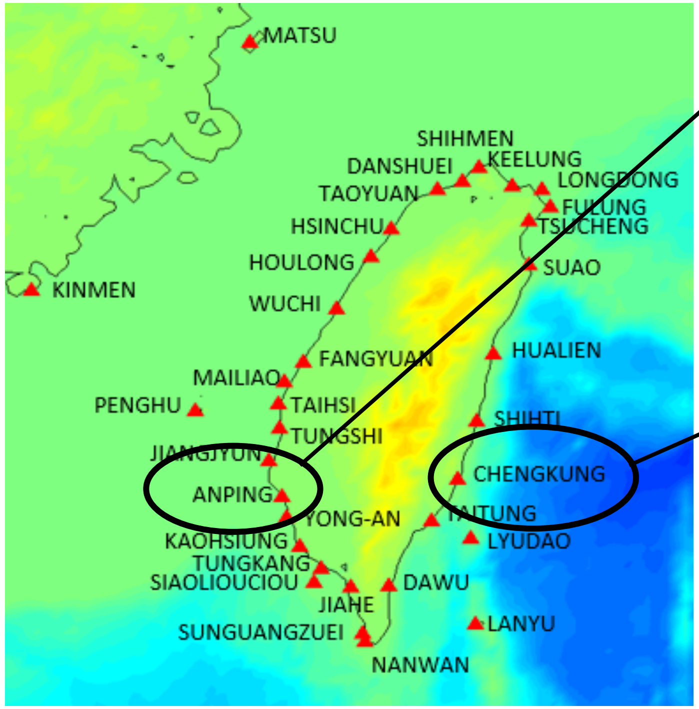


Pressure Gradient (Nanwan)

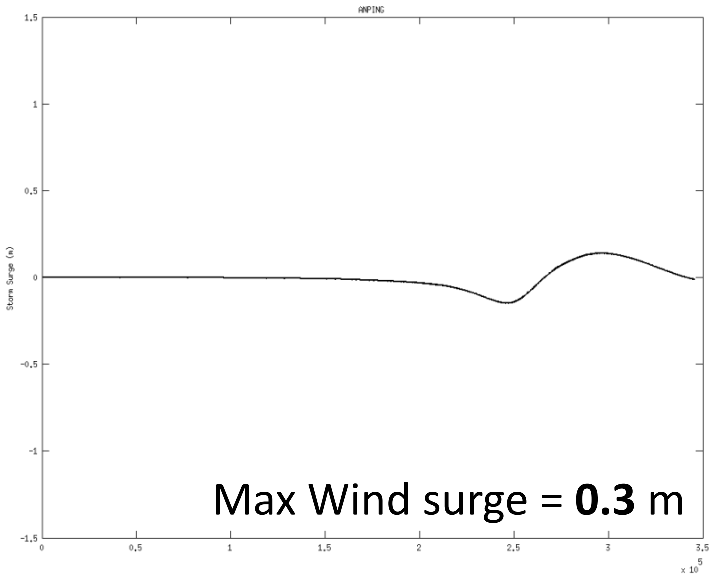


Contribution of Wind Shear Stress and Pressure Gradient

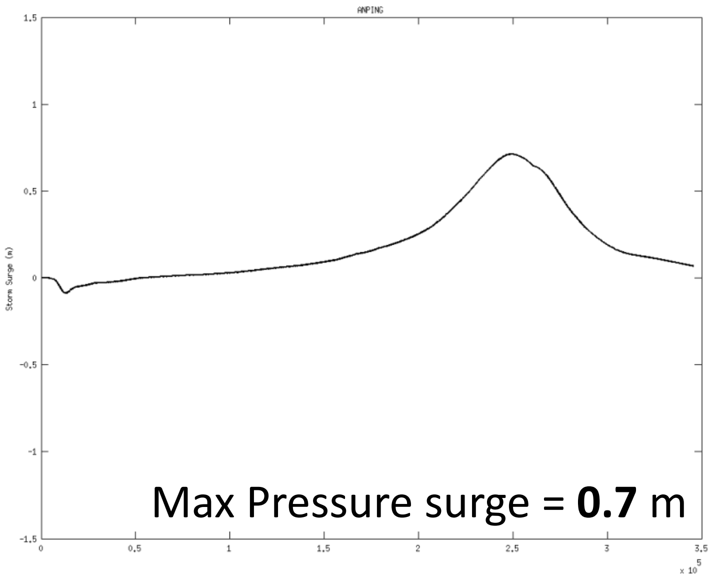
2016 Typhoon Meranti



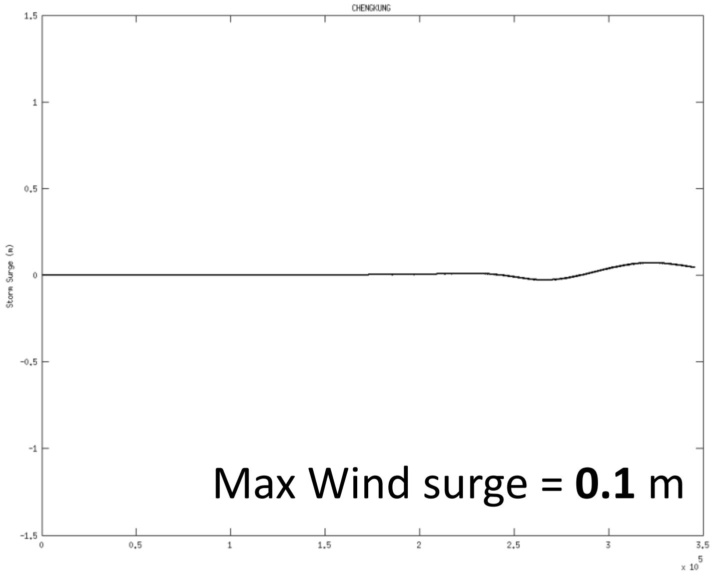
Wind Shear Stress (Anping)



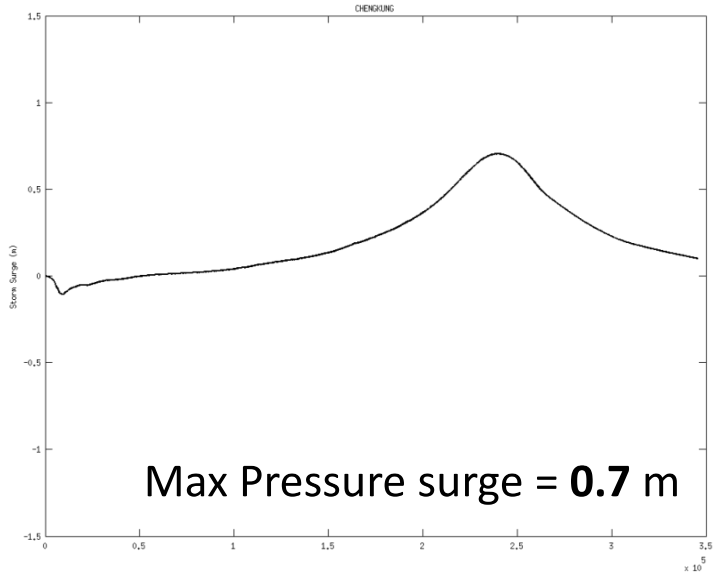
Pressure Gradient (Anping)



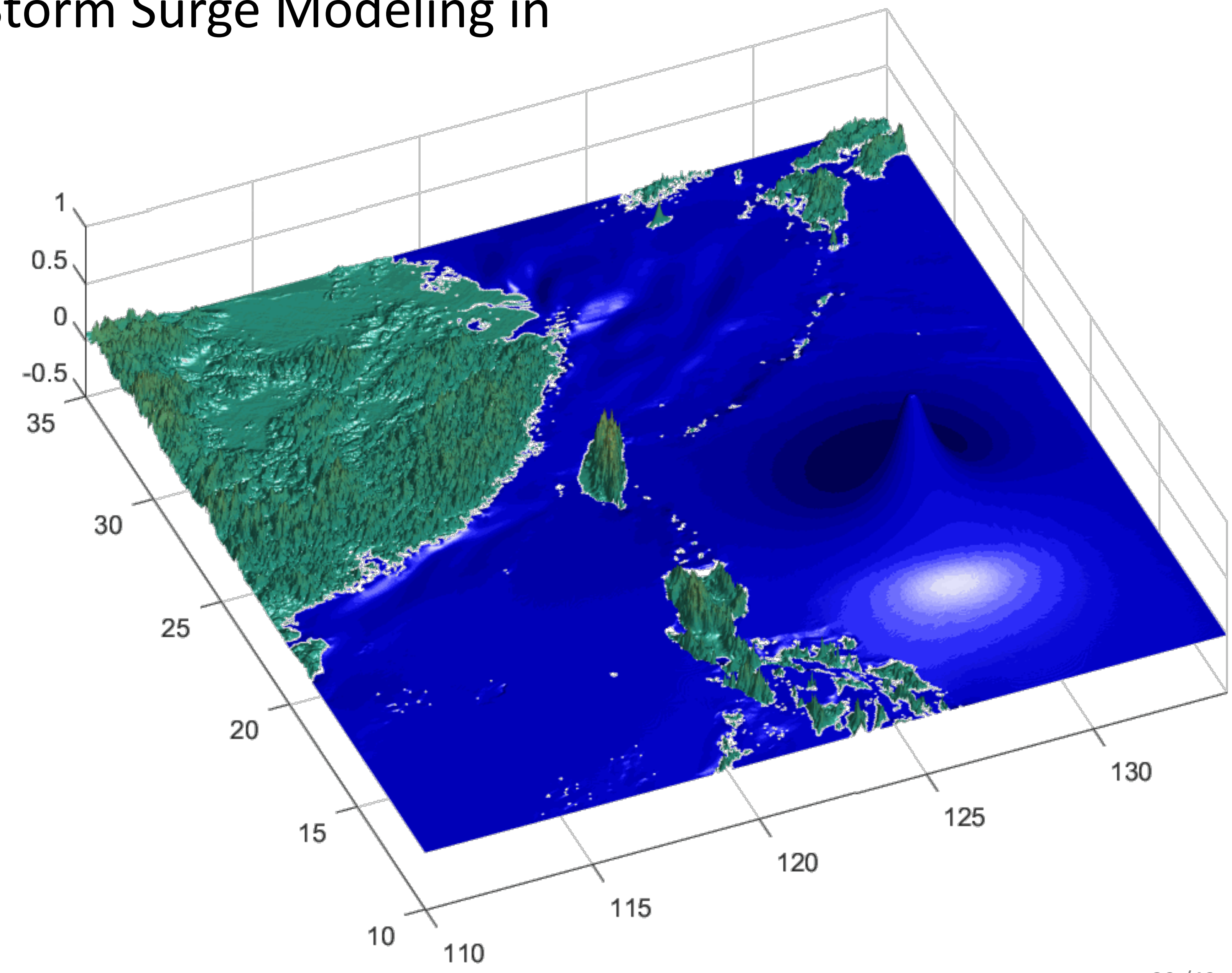
Wind Shear Stress (Chengkung)



Pressure Gradient (Chengkung)

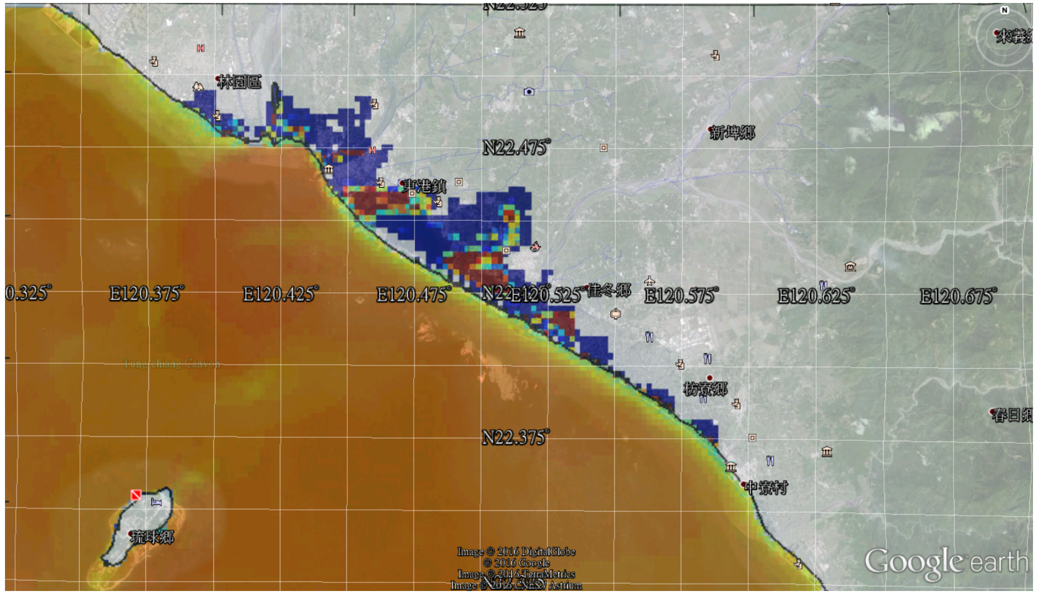


3-D Demonstration of Storm Surge Modeling in Deep-water Regions

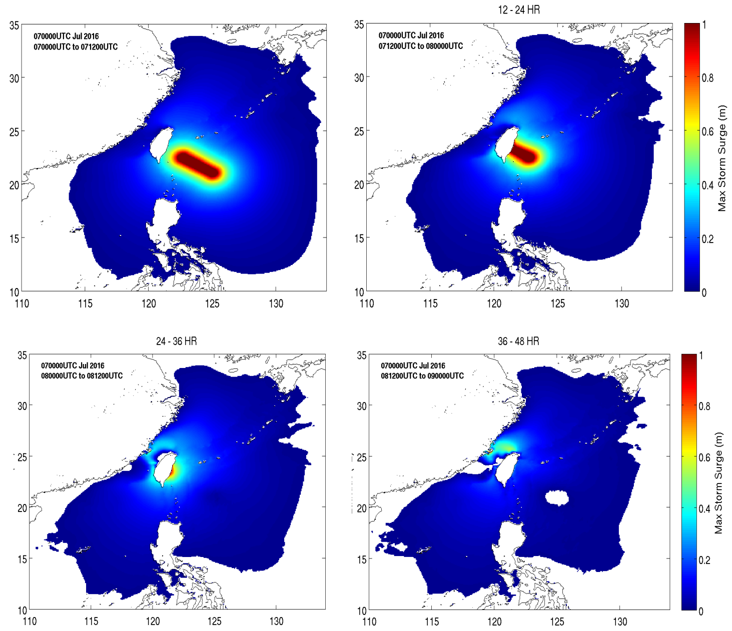


Storm Surge Model Products

- **High-Resolution Potential Inundation Area**
  - Storm Surge Inundation Area
  - Pure Tide Inundation Area
- **Predicted Water Elevations at Specified Tidal Stations**
  - Storm Surge
  - Tide
  - Storm Tides (Storm Surge + Tide)
- **Maximum Water Elevations in Coastal Regions**
  - Maximum Storm Surge
  - Maximum Tide
  - Maximum Storm Tide (Storm Surge + Tide)



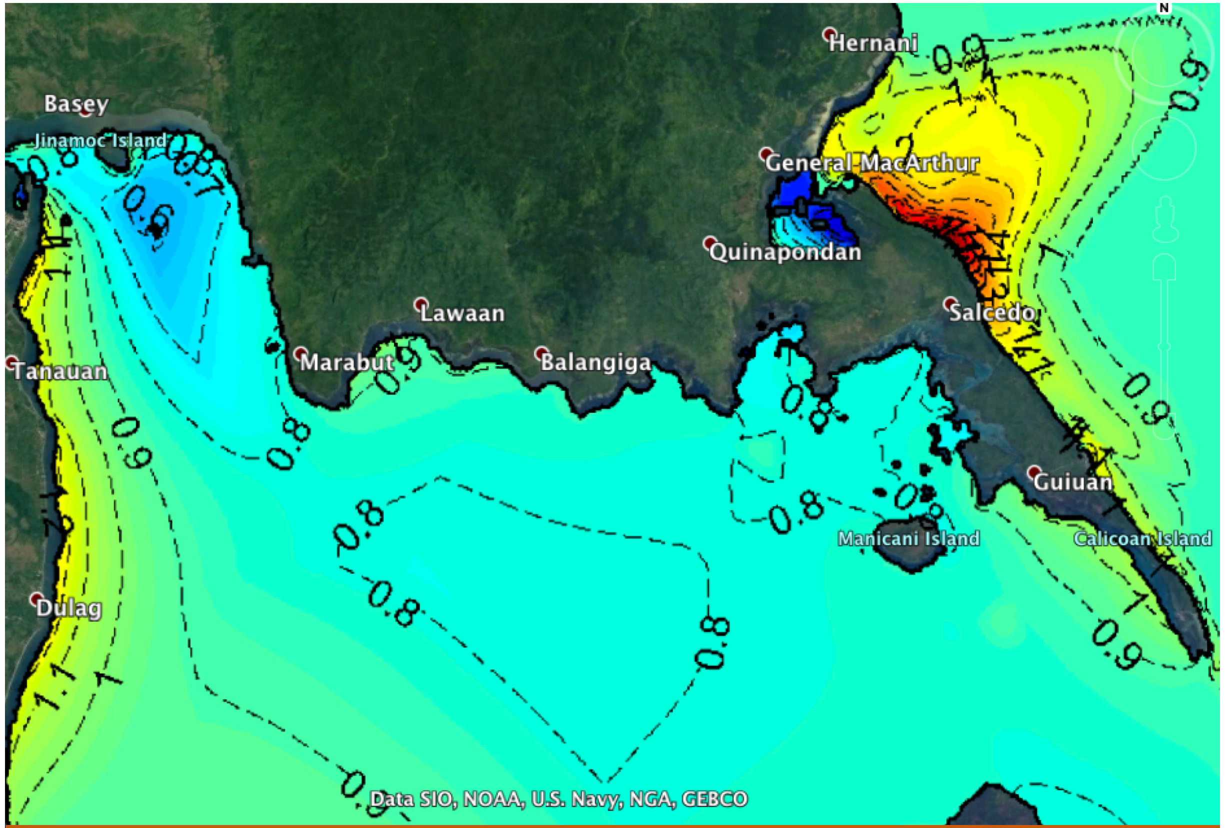
High-Resolution Surge Inundation



Maximum Storm Surge

Conclusion

- Our CWB COMCOT storm surge model :
  - ✓ Adopt the **large computational domain** to cover the complete typhoon life cycle and full storm surge propagation.
  - ✓ The resolution in coastal regions can be promoted easily and be separately calculated in **nested-grid scheme**.
  - ✓ Combine with the **dynamic atmospheric WRF/ TWRF model**.
  - ✓ Combine 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 Central Weather Bureau from 2016.



Maximum Simulated Storm Tides at Leyte Gulf, Philippines.

Thanks for your listening.
Welcome for comments and questions.