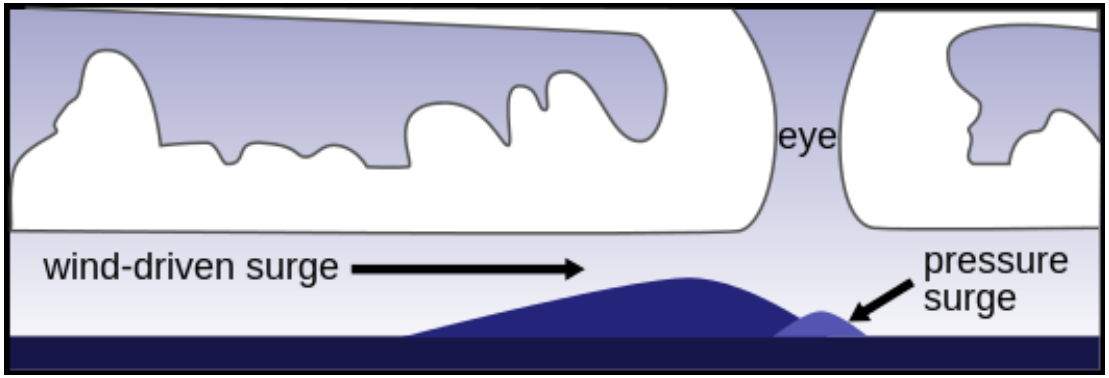
International Symposium on Grids and Clouds (ISGC)
Environmental Computing Workshop

Storm Surge Modeling and Case Study of 2013 Super Typhoon Haiyan

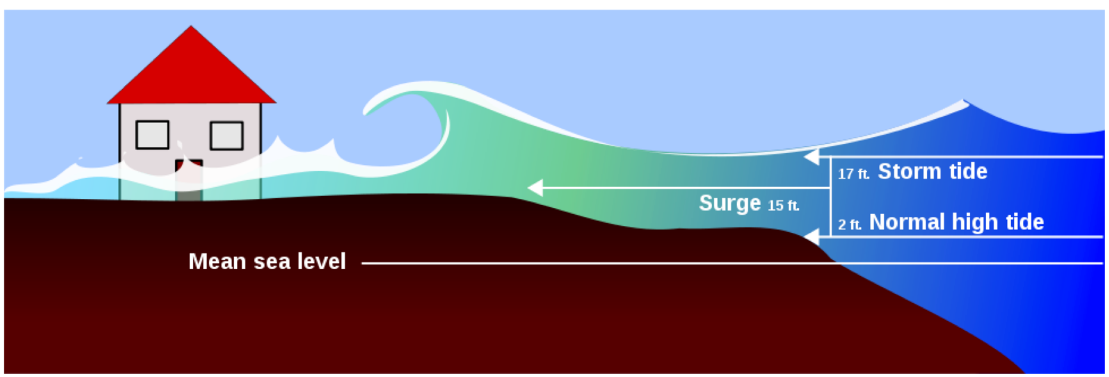
Yu-Lin Tsai[1], Tso-Ren Wu[1], Simon C. Lin[2], Chuan-Yao Lin[3], Eric Yen[2]

[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

STORM SURGE



Sea Surface induced by typhoons (NHC, NOAA)



Tidal Effect with Storm Surges (NHC, NOAA)

- Storm surge is a abnormal water level rising induced by low pressure weather systems in open ocean or coastal regions :
  - ✓ **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

2005 Hurricane Katrina (USA)

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

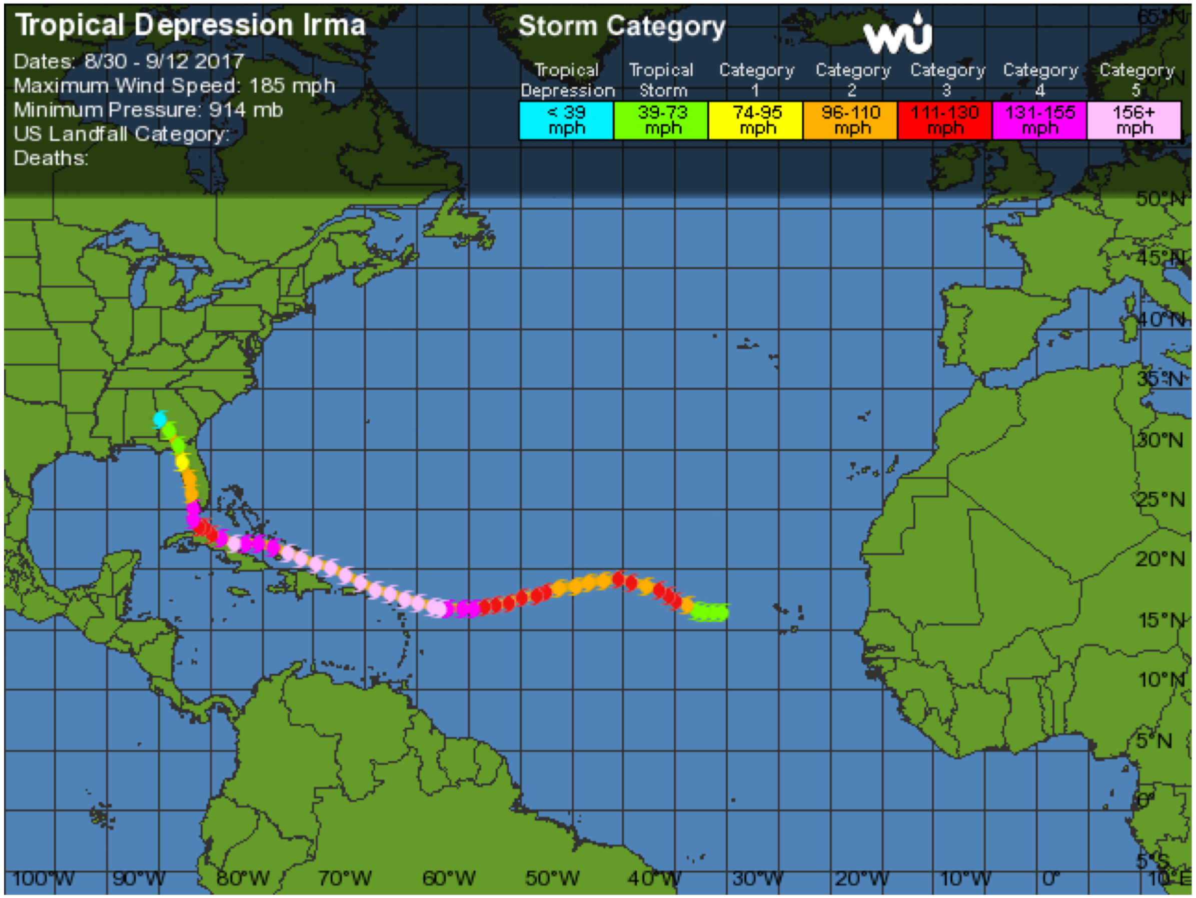
Views of inundated areas in New Orleans following breaking of the levees surrounding the city as the result of storm surge from Hurricane Katrina - 2005

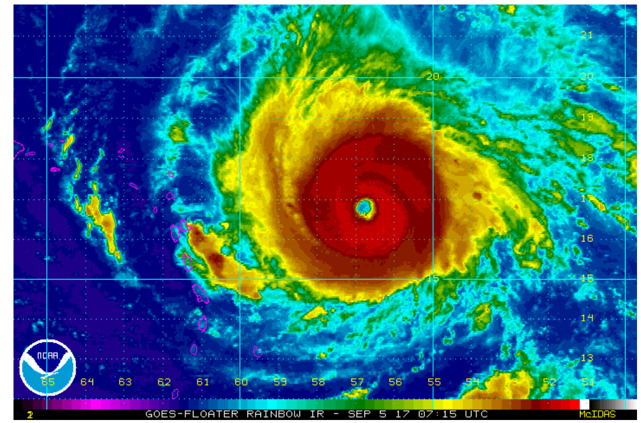
Inundation induced by 2005 Hurricane Katrina. (http://www.stormsurge.noaa.gov/)

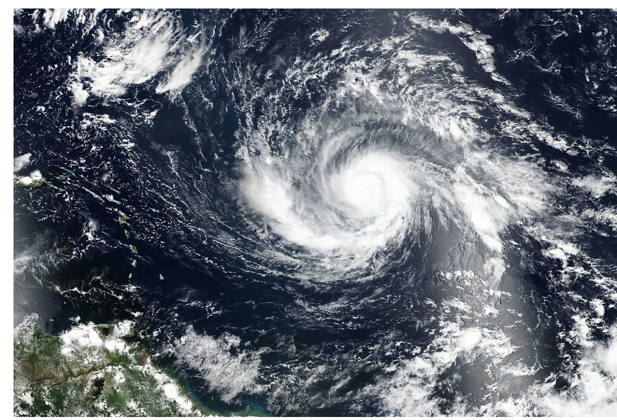
Flooded by storm surge of Hurricane Katrina (2005) in the northwest New Orleans.

2017 Hurricane Irma (USA)

2017.09.01 – 2017.09.13

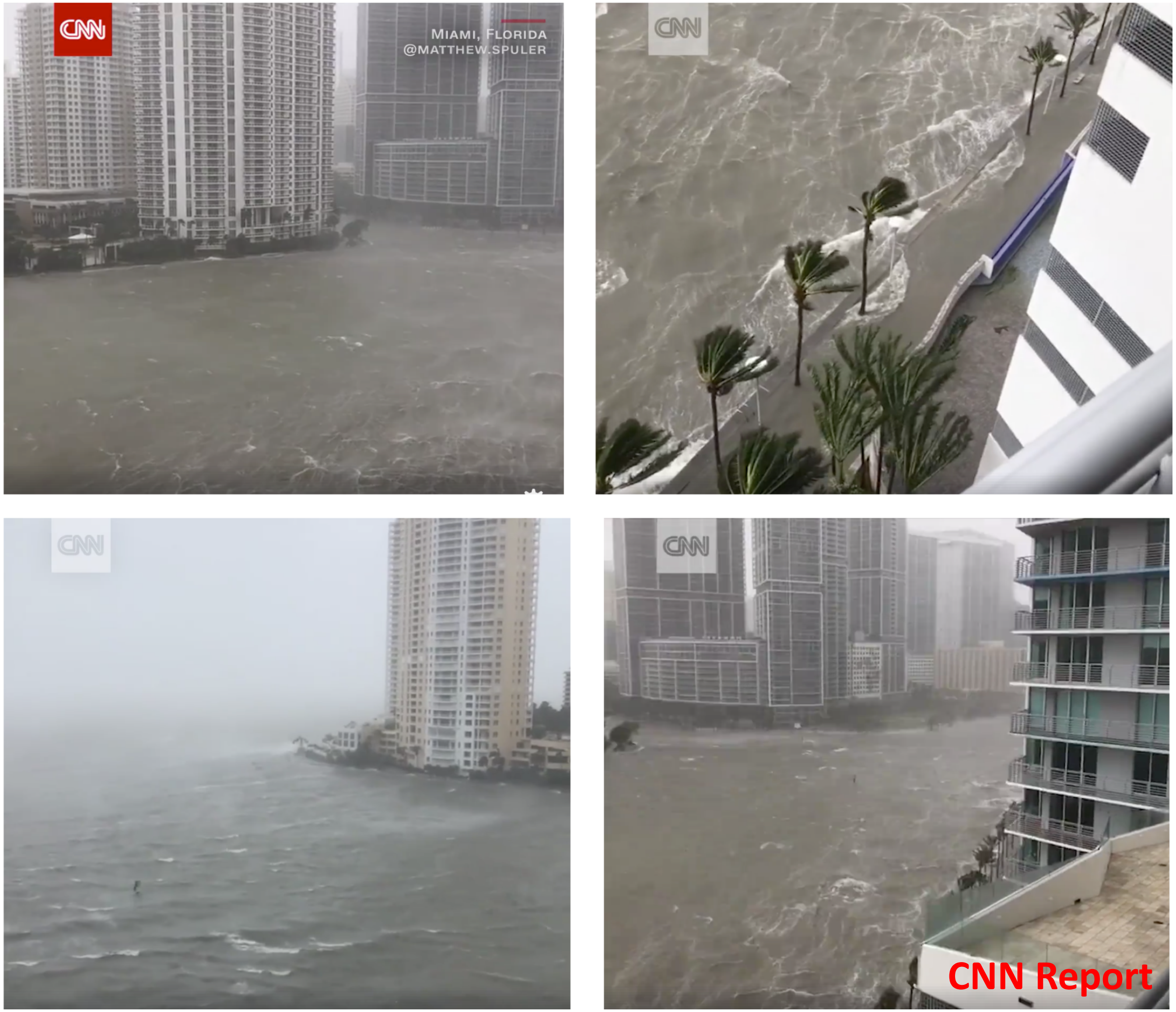






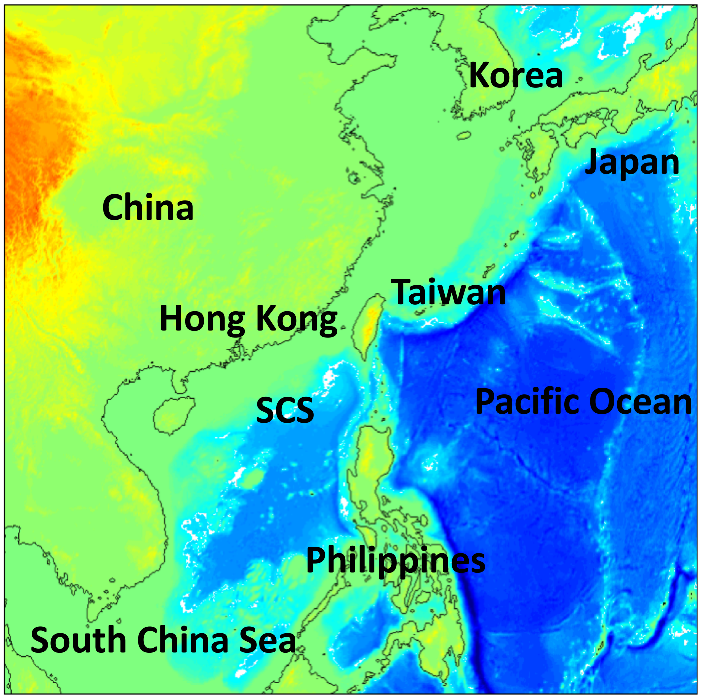
Suomi NPP/VIIRS satellite view of Hurricane Irma on 03 September 2017. Resolution: 1px=1km.

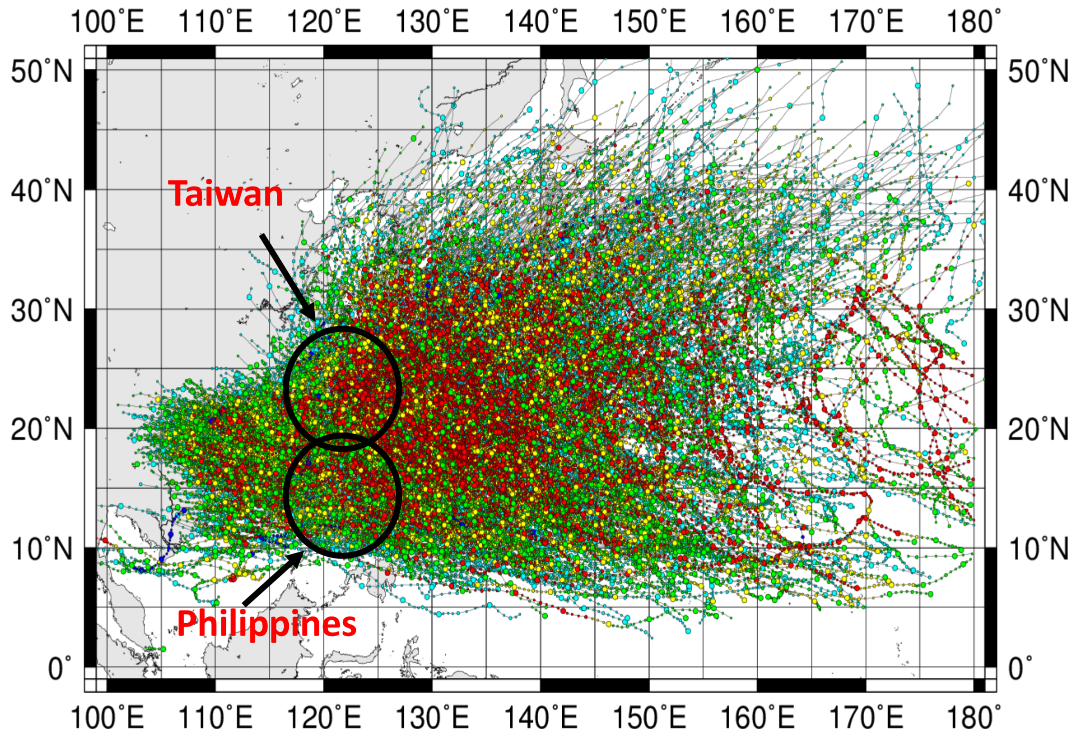
Storm Surge and Wave in Miami



https://www.facebook.com/cnn/videos/10157293993976509/?hc_ref=ARR5mV07Uvi7HUJj24o11m3wBF8NwzTqeorWgjeOGoAhT5cKInnkDzro4bZ1Qb0z8WQ&fref=gs&dti=143043675792340&hc_location=group

Tropical Cyclones in East Asia

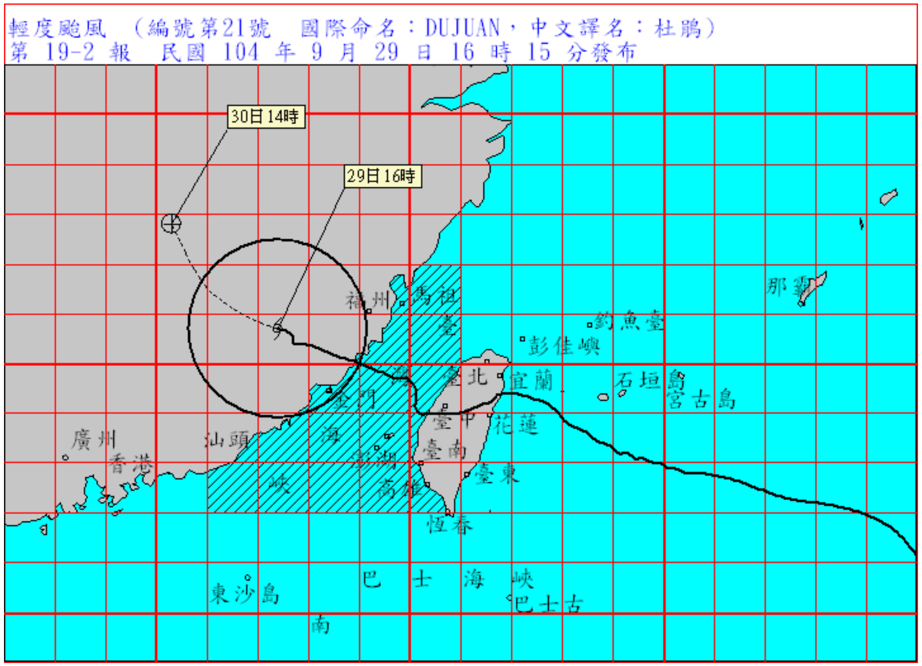




Tracks of all tropical cyclones in the northwestern Pacific Ocean between 1951 and 2014.

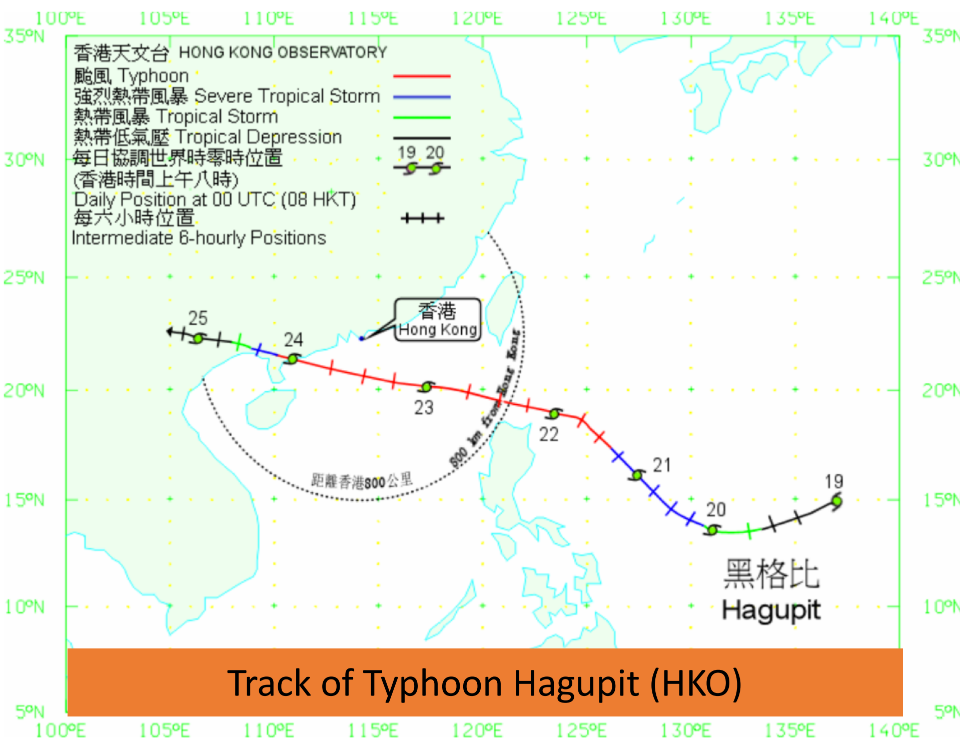
Taiwan – Catogory-4 Typhoon Dujuan

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

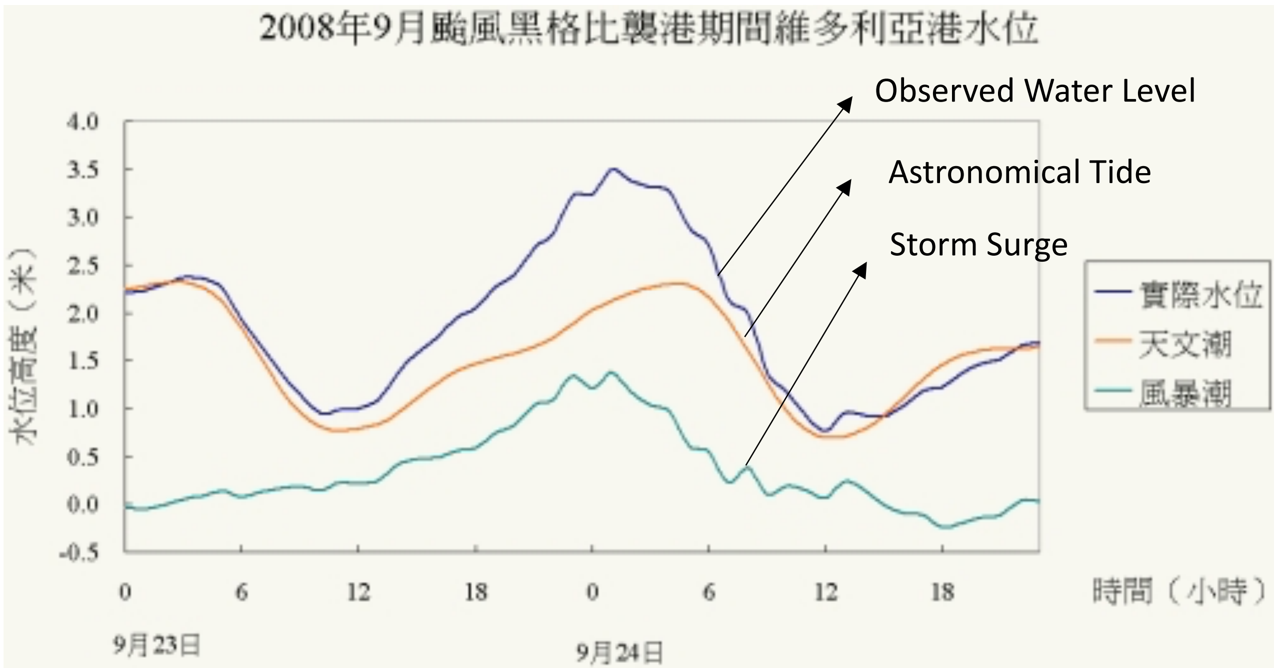


Track of Typhoon Hagupit (HKO)

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

Super Typhoon

- **"Super-typhoon"** is a term utilized by the U.S. Joint Typhoon Warning Center for typhoons that reach maximum sustained 1-minute surface winds of at least 65 m/s (130 kt, 150 mph).

- This is the equivalent of a strong Saffir-Simpson category 4 or category 5 hurricane in the Atlantic basin or a category 5 severe tropical cyclone in the Australian basin.

- Would climate change induce more super typhoons?

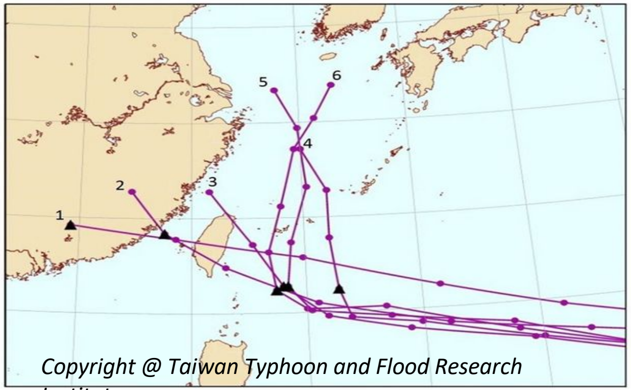
Super Typhoons in Western North Pacific Ocean (2010 - 2016)

			10-min Maximum Wind Speed	Minimum Central Pressure
Megi	2010	Category 5 super typhoon	230 km/h (145 mph)	885 hPa (26.13 inHg)
Sanba	2012	Category 5 super typhoon	205 km/h (125 mph)	900 hPa (26.58 inHg)
Haiyan	2013	Category 5 super typhoon	230 km/h (145 mph)	895 hPa (26.43 inHg)
Vongfong	2014	Category 5 super typhoon	215 km/h (130 mph)	900 hPa (26.58 inHg)
Soudelor	2015	Category 5 super typhoon	215 km/h (130 mph)	900 hPa (26.58 inHg)
Nepartak	2016	Category 5 super typhoon	205 km/h (125 mph)	900 hPa (26.58 inHg)
Meranti	2016	Category 5 super typhoon	220 km/h (140 mph)	890 hPa (26.28 inHg)
Haima	2016	Category 5 super typhoon	215 km/h (130 mph)	900 hPa (26.58 inHg)

https://en.wikipedia.org/wiki/List_of_the_most_intense_tropical_cyclones

Goals for a Storm Surge Model

- 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

Multi-Scale Storm Surge Propagation (NOAA)

The Introduction of 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.

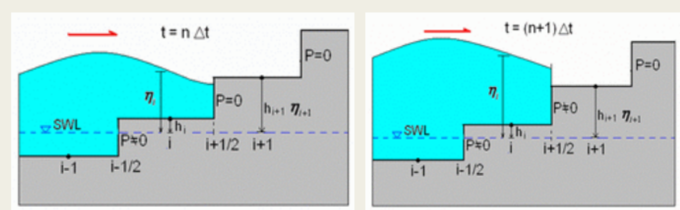


Fig.02 Moving Boundary Scheme

(1). NOAA Benchmark Problem Validation

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

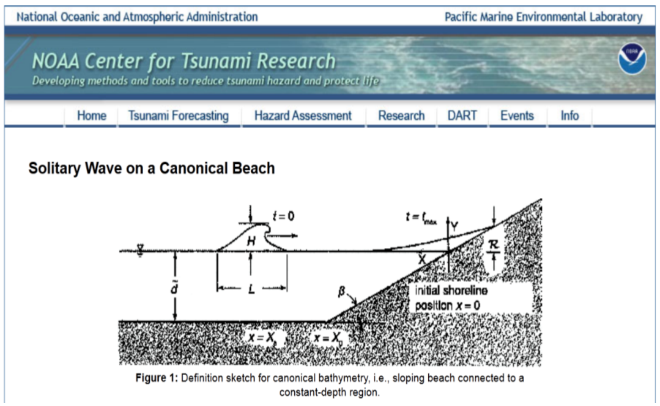
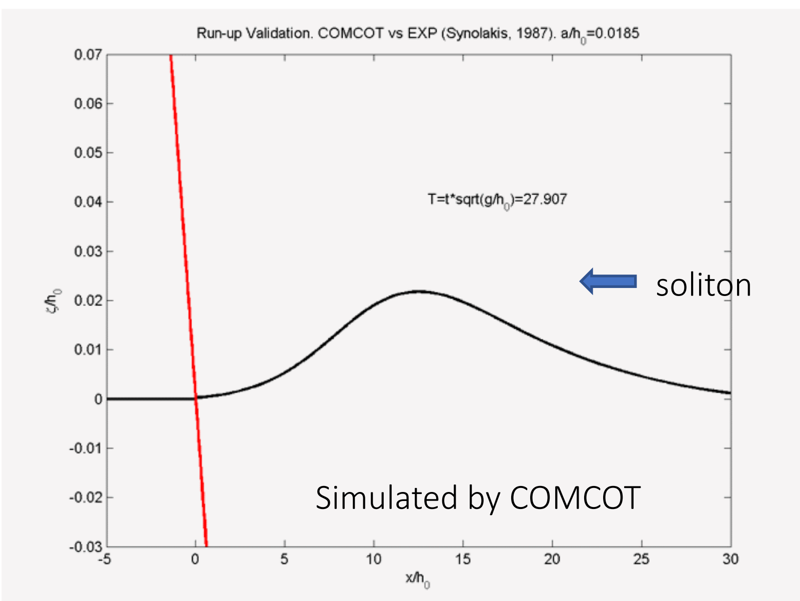
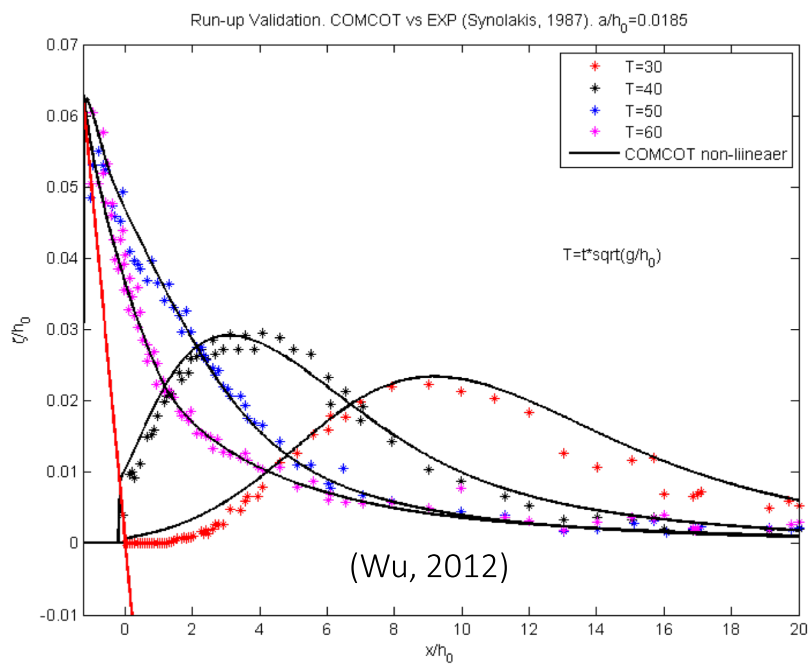


Figure 2: Time evolution of H = 0.0185 initial wave over a sloping beach with $\cot\beta = 19.85$ from $t = 25$ to 65 with 10 increments. Constant depth-segment starts at $X_0 = 19.85$. While markers show experimental results of Synolakis (1986, 1987), solid lines show nonlinear analytical solution of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

(from NOAA Official Website)



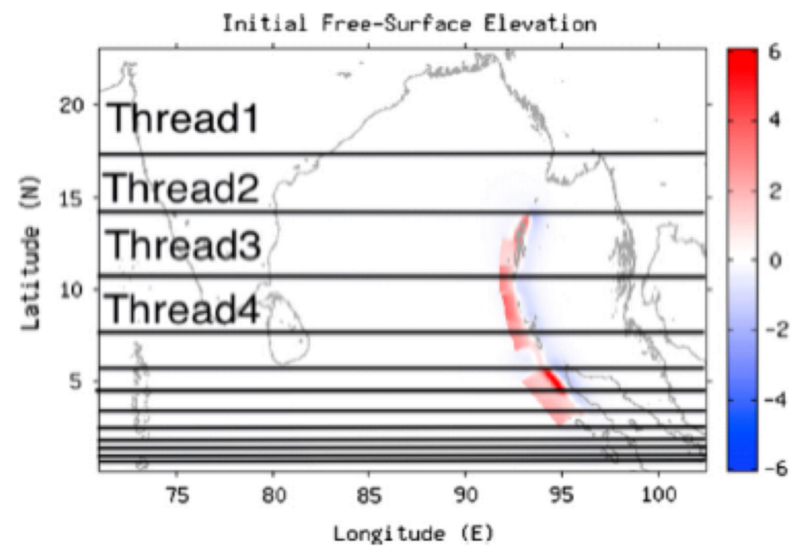


(2). High-speed Calculation

COMCOT-Surge Model can finish 48 hrs forecast in 30 mins on PC-level computational resources 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.

ELSEVIER
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]

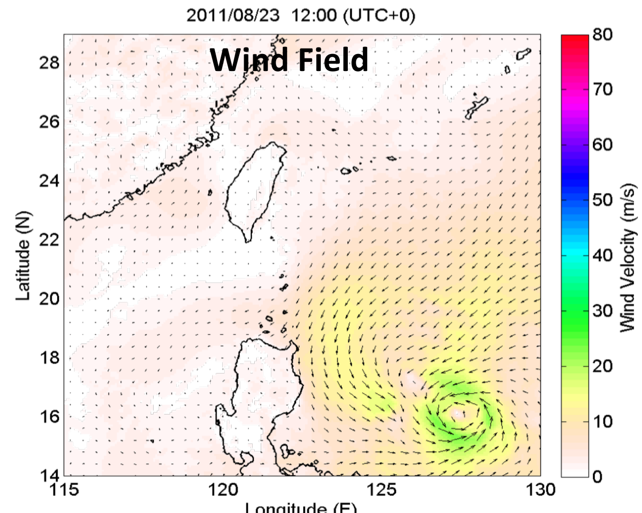
[a] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
[b] Academia Sinica Grid Computing Centre, Taipei 11529, Taiwan
[c] Institute of Hydrological & Oceanic Sciences, National Central University, Jhongli 32001, Taiwan
[d] School of Civil and Environmental Engineering, Cornell University, Ithaca,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

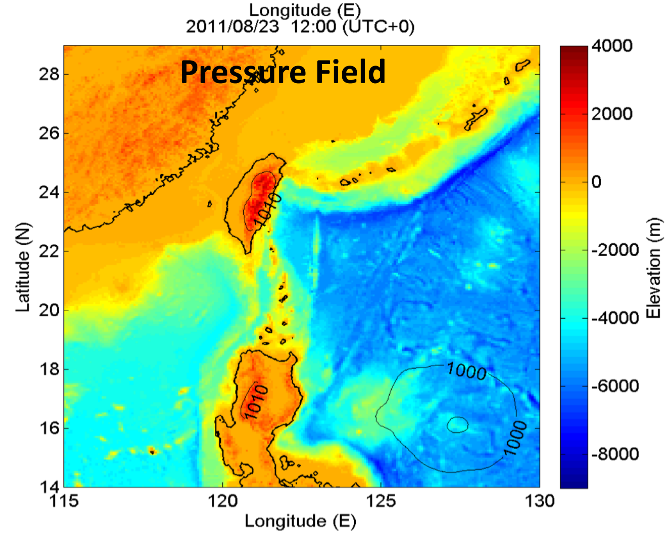
*The results has been published on Ocean Engineering (**Simon C. Lin** et al., 2015).*

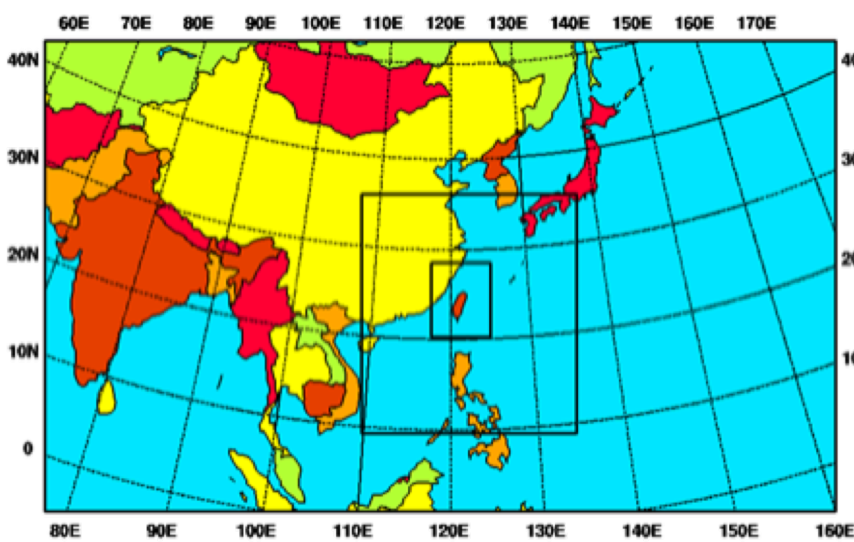
(3). Combine with the Atmospheric Model

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.



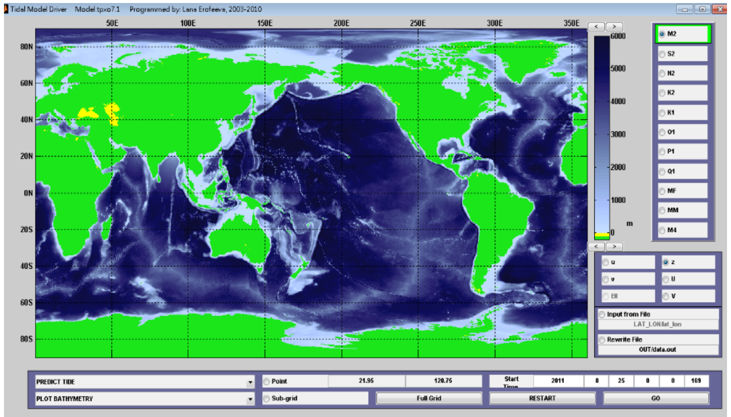




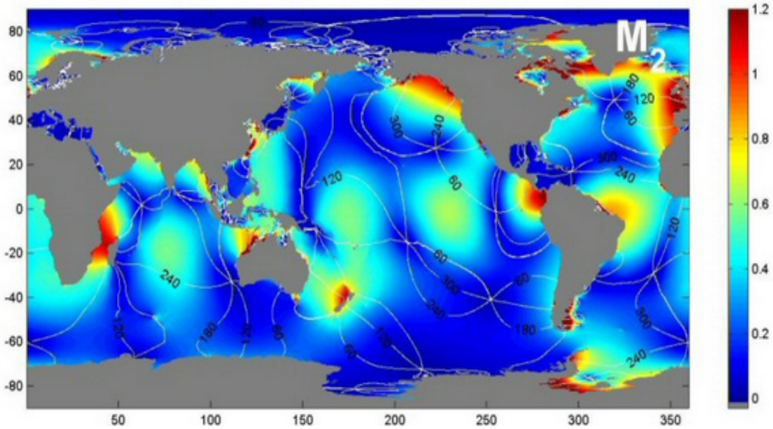
WRF Computational Domain (CWB)

(4). Combine with Global Tide TPXO Model

(USA OSU TOPEX/POSEIDON Global Tidal Model)



User Interface of TPXO



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]

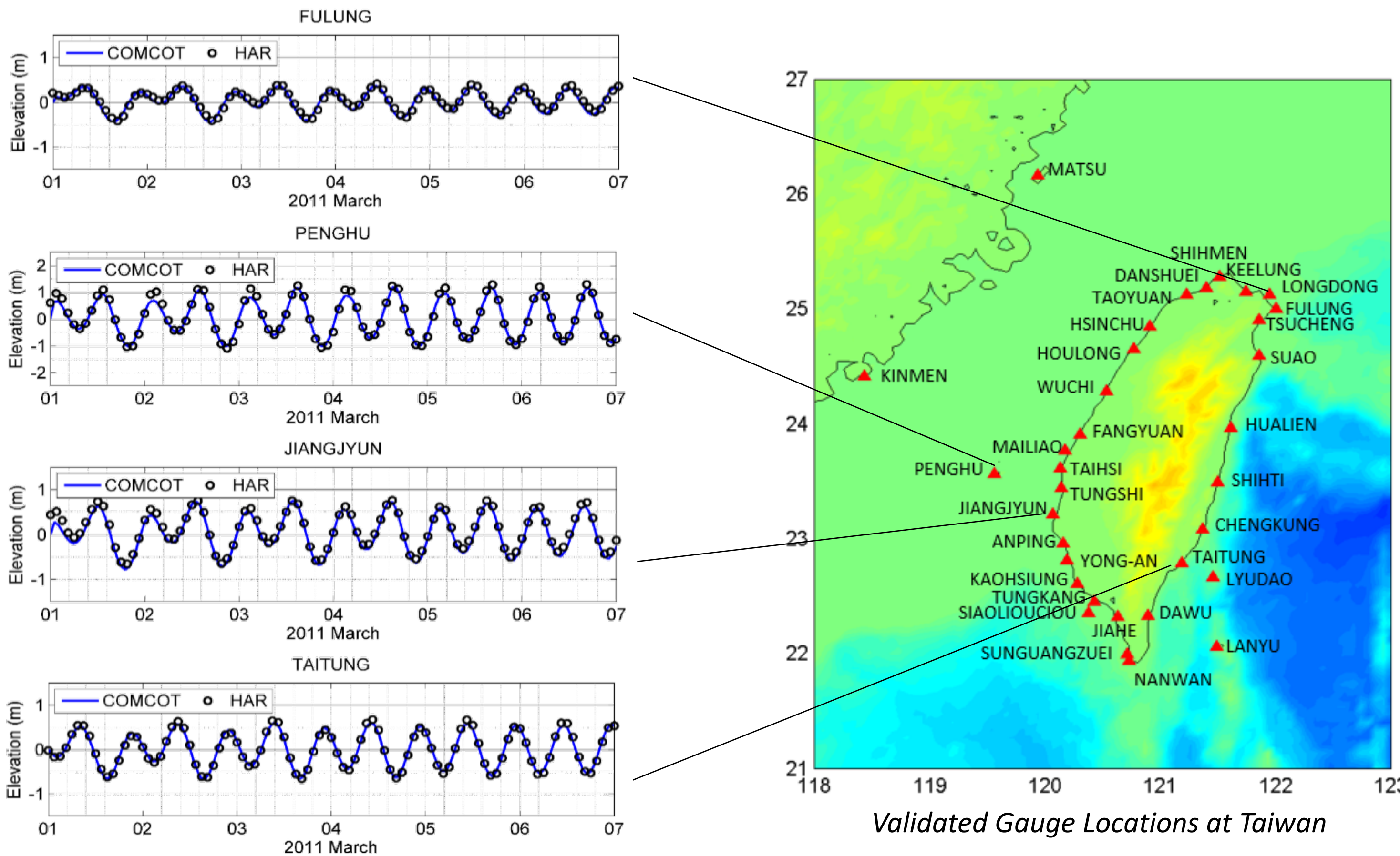
[1]*Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, Seattle, WA, U.S.A.*
[2]*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, U.S.A.*
[3]*Scripps Institution of Oceanography, La Jolla, CA, U.S.A.*
[4]*Department of Electrical 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 ($3–8 \times 10^{-9}$ 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)

(5). High-Accuracy Tide Simulation

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



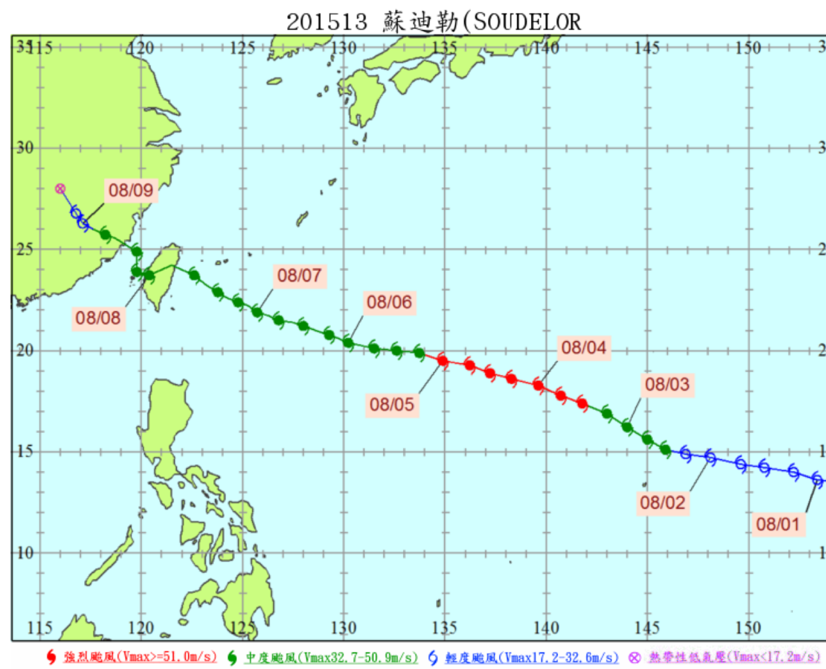
Validated Gauge Locations at Taiwan

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

Surge Surge Induced by 2015 Super 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.

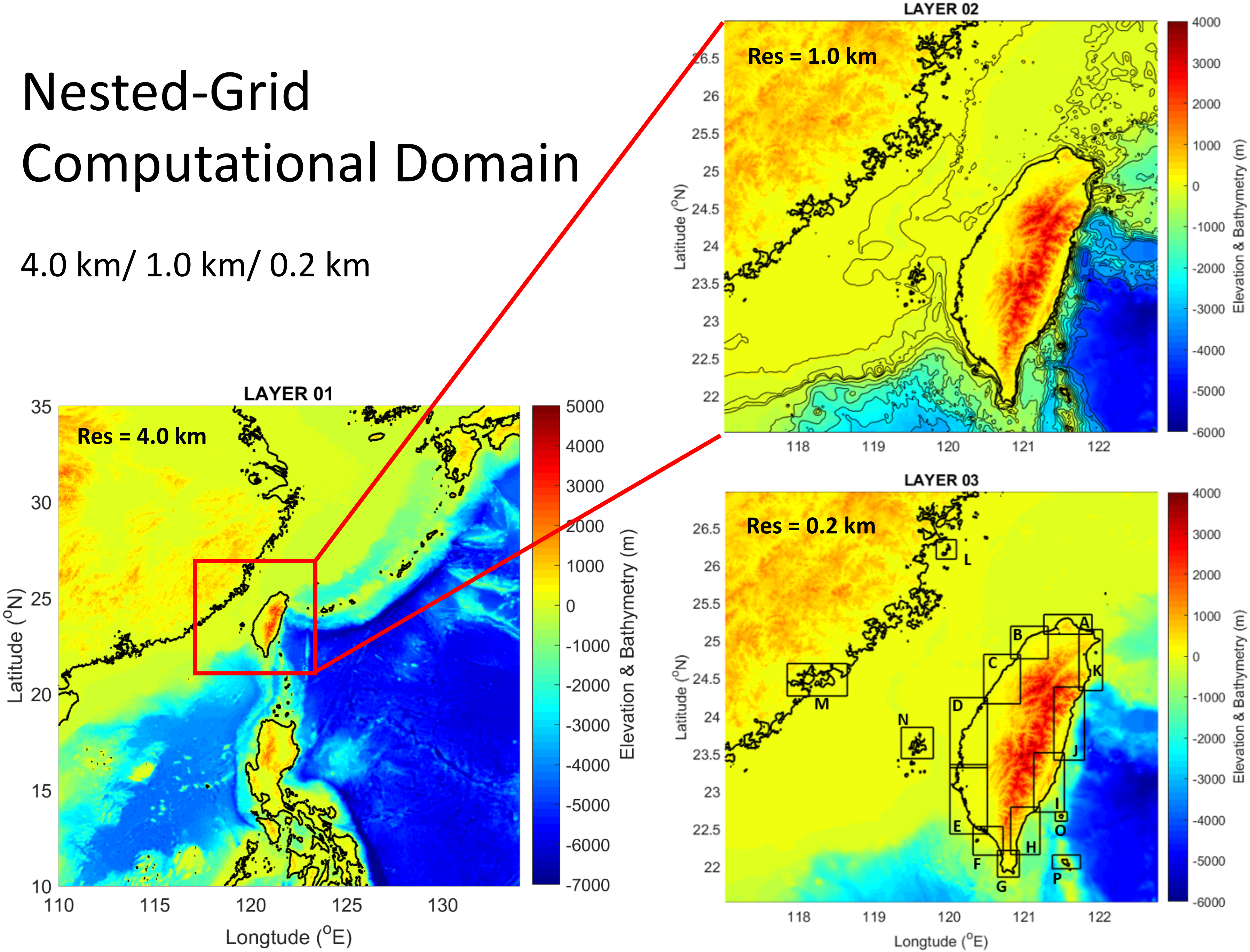
The flood in low-lying region at Ilan because of Typhoon Soudelor. (中央社記者沈如峰宜蘭縣)



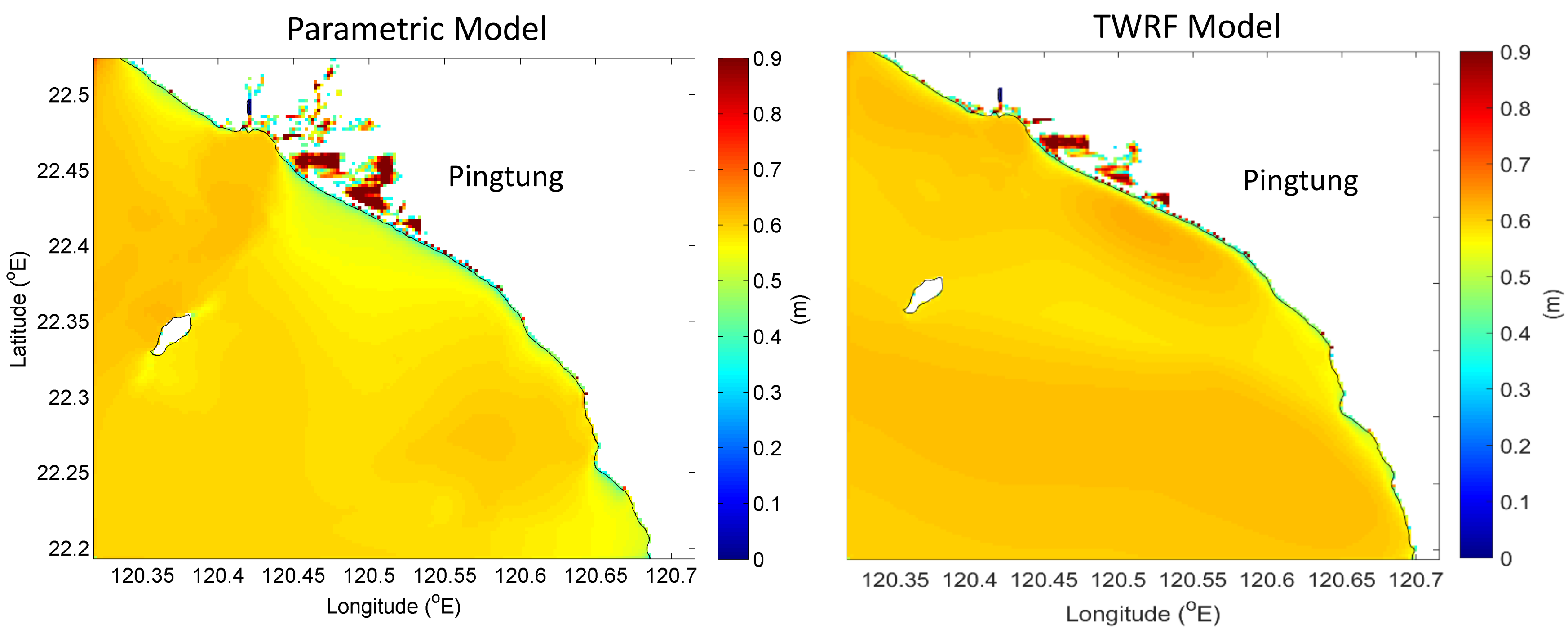
（資料來源：中央氣象局颱風資料庫）

Nested-Grid Computational Domain

4.0 km/ 1.0 km/ 0.2 km



Coastal Inundation Calculation

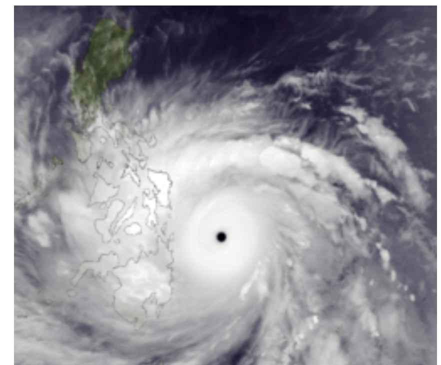


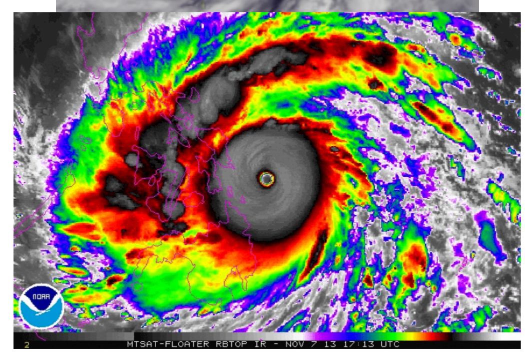
Our COMCOT storm surge model could also calculation the inundation area with nonlinear shallow water equations which considers nonlinear effects, bottom effects, and Coriolis effects inside.

2013 Super 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

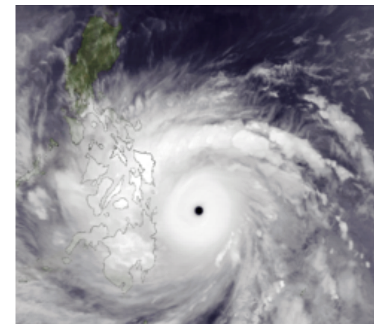
1) Inundation height was measured at **5.9 m** near the San Juanico Bridge.

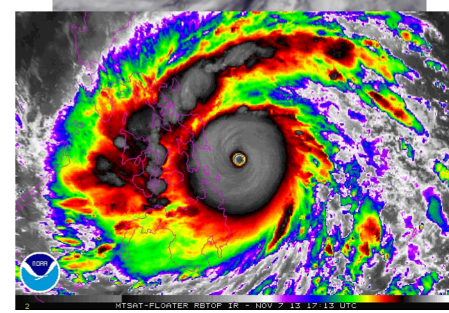
2) Sea wall damage at Tagpuro and the run-up height was about **6.9 m**.

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.)

Track of Super 2013 Typhoon Haiyan

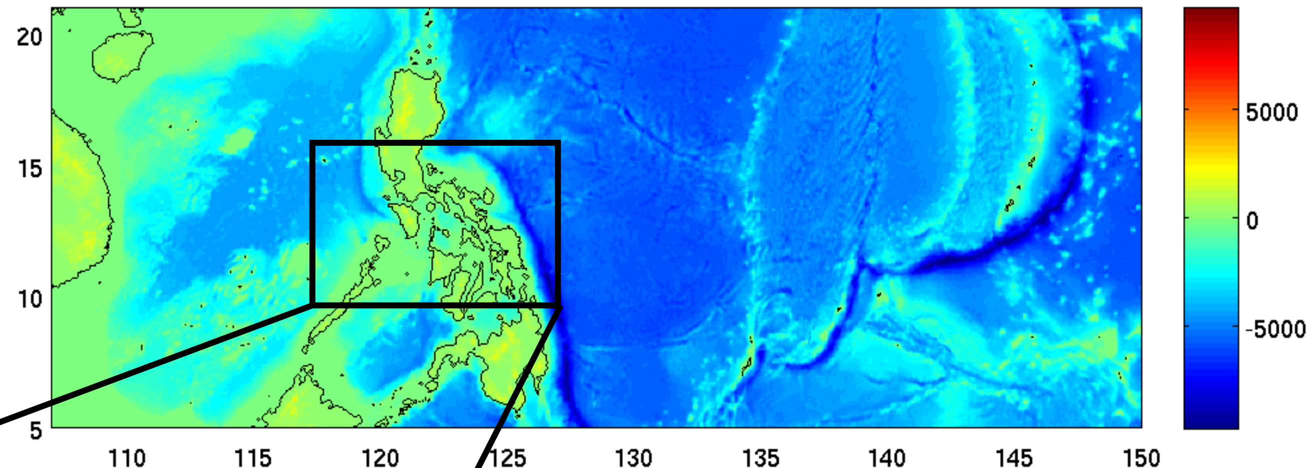




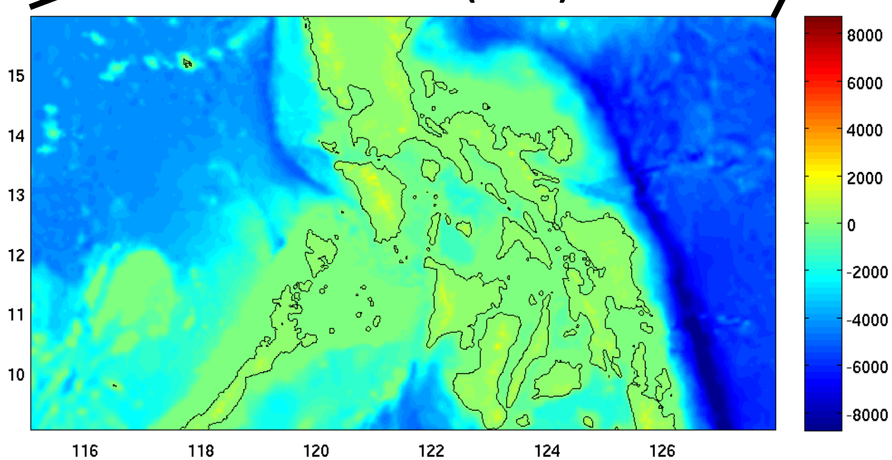
Source: Hong Kong Observatory

Nested Computational Domain for Haiyan Case

LAYER 01 (4 km)



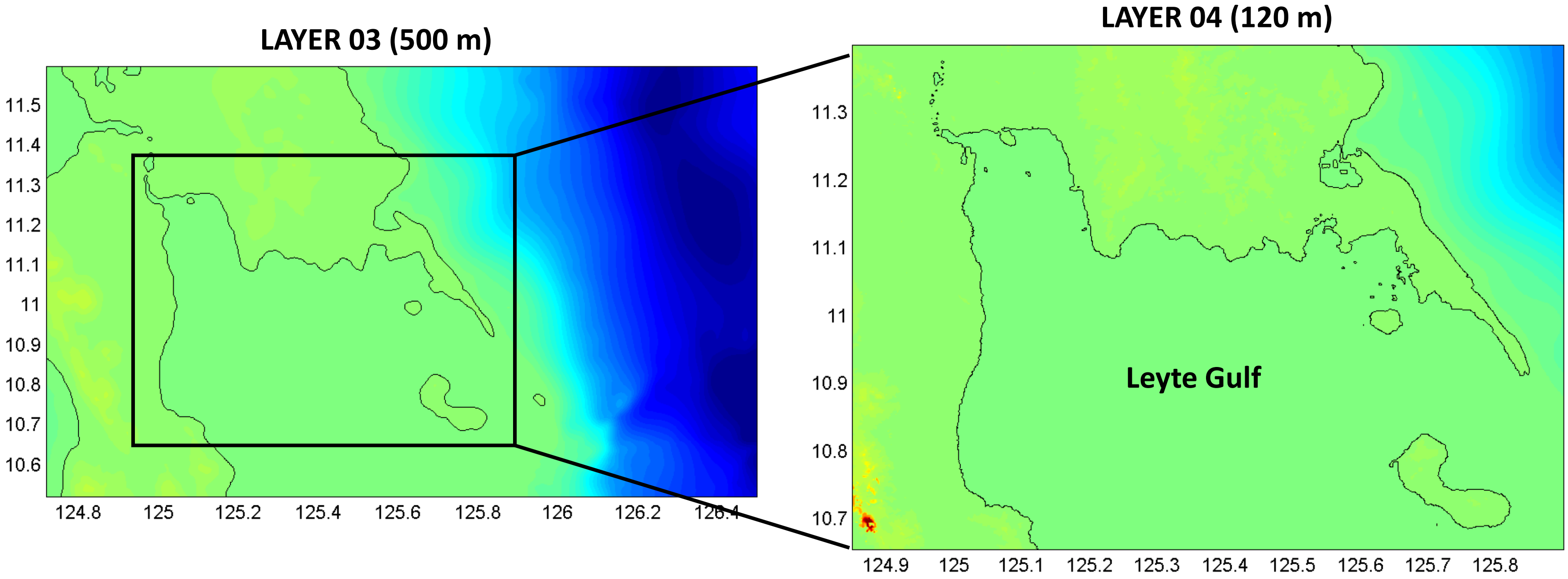
LAYER 02 (1 km)



- 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.

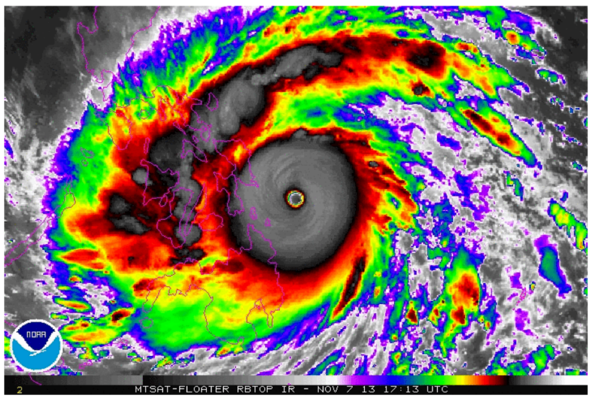
Near-shore Computational Domain

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



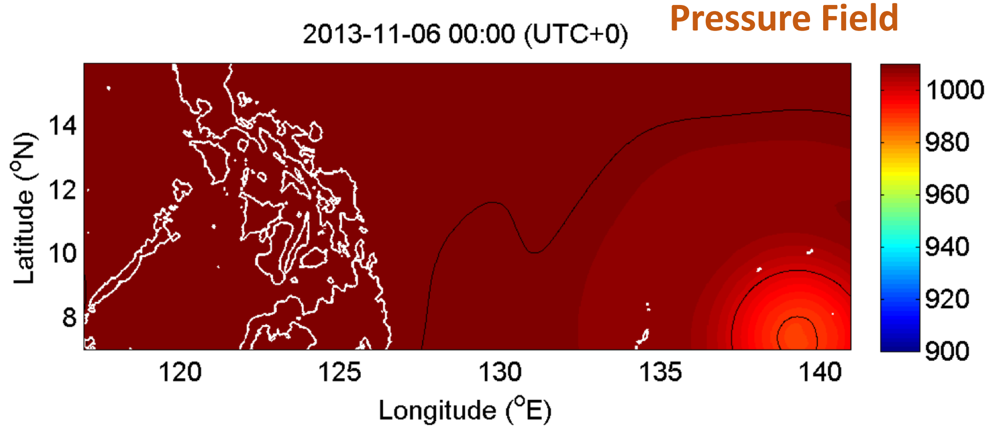
The computational domain of Layer 03 and Layer 04 could cover the storm surge propagations in offshore and nearshore regions.

Combine with the Atmospheric WRF Model

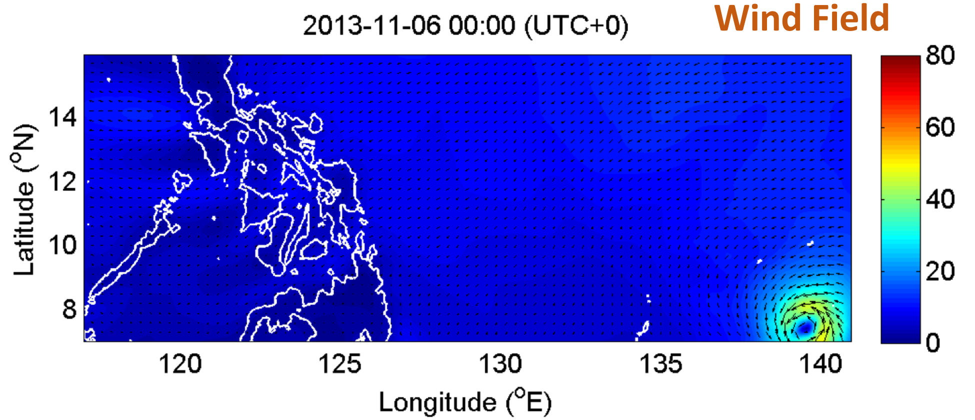


- *Asymmetric effect*
- *Topographic effect*
- *Hydrodynamic Pressure*

Pressure Field



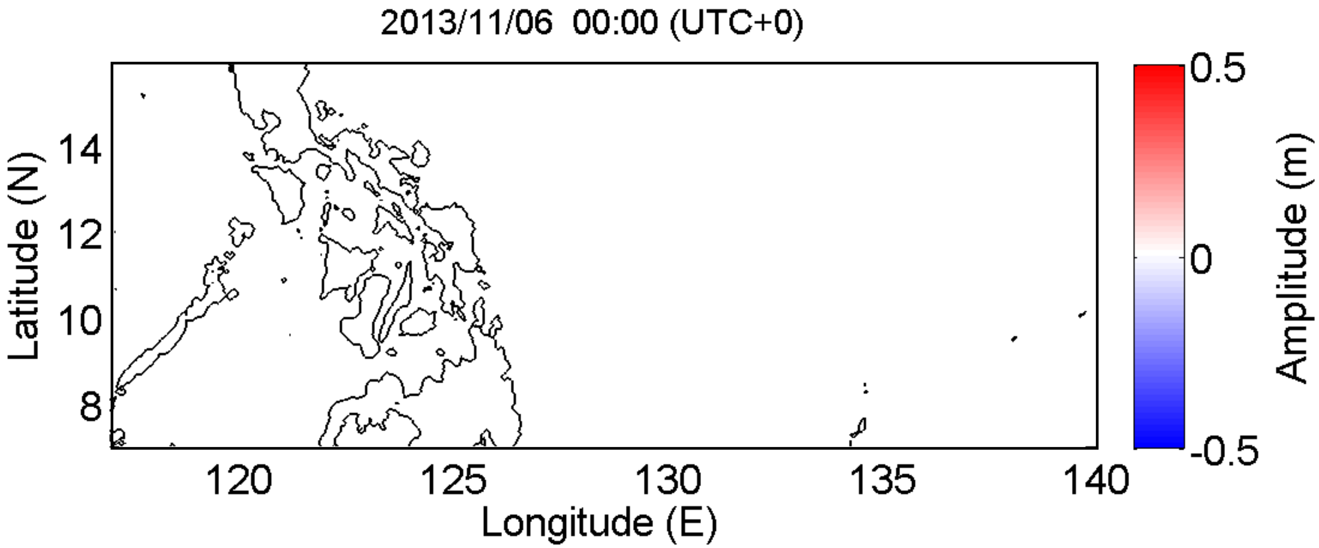
Wind Field



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

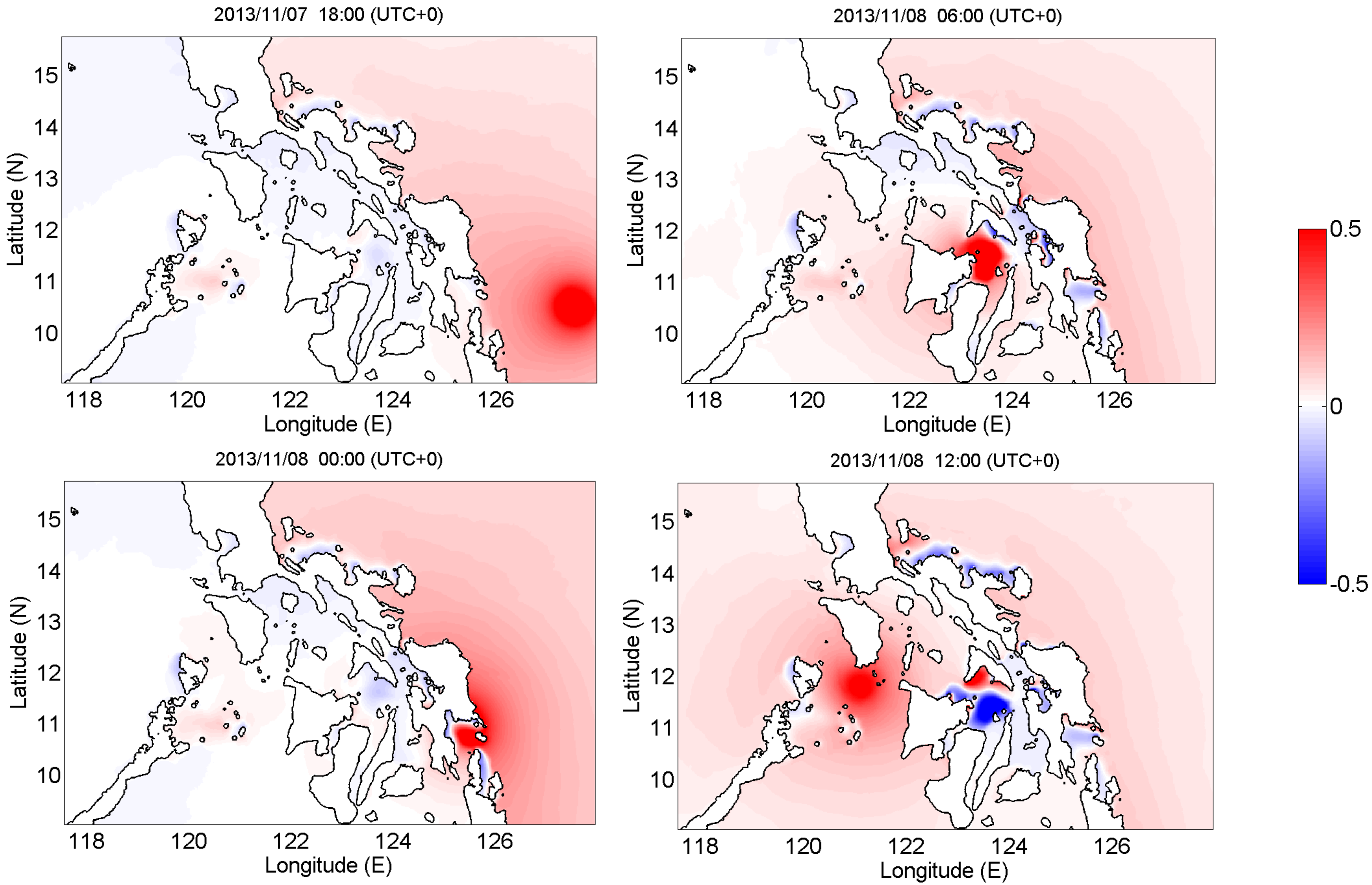
Storm Surges Induced by Typhoon Haiyan

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

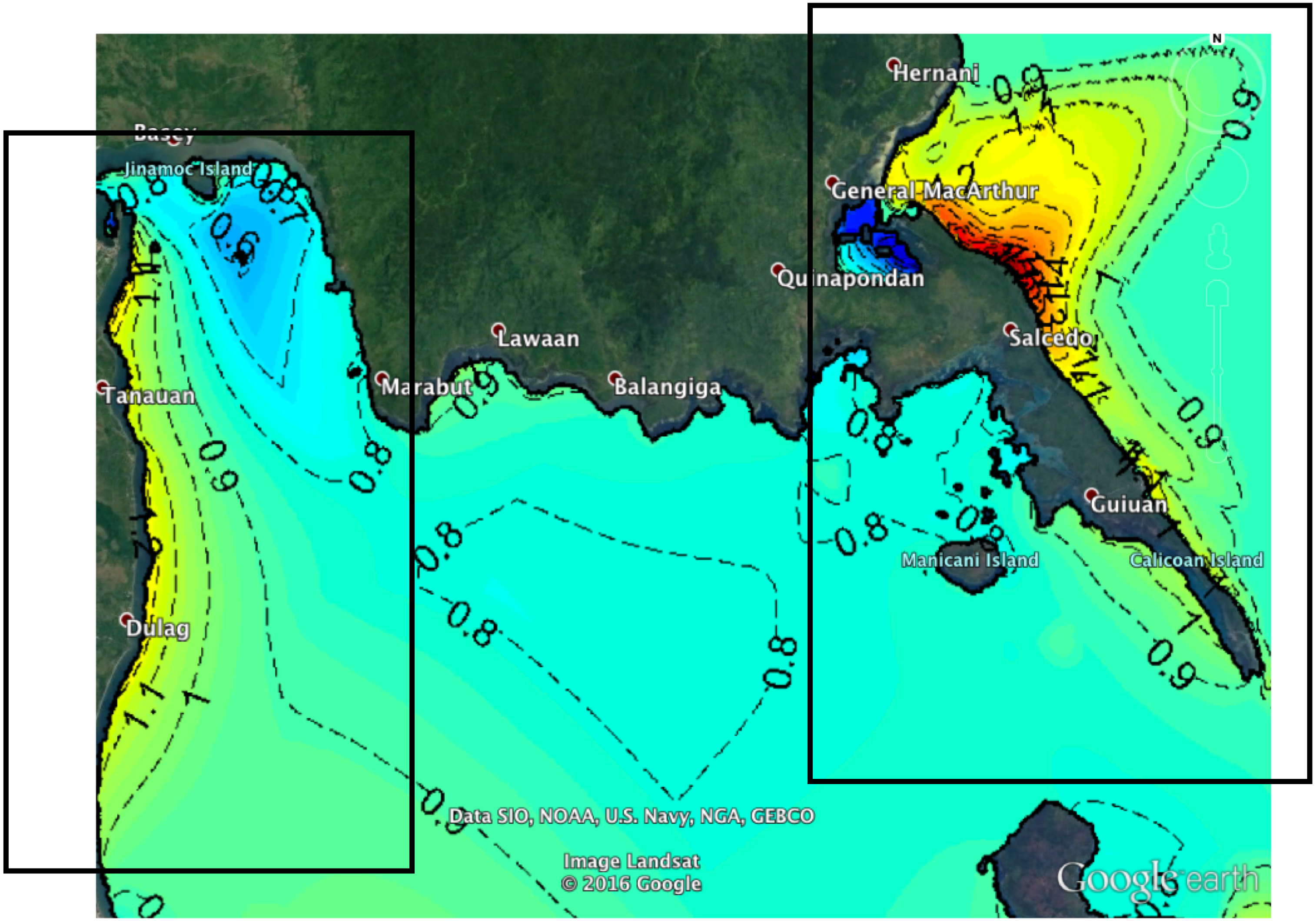


Large computational domain to cover the complete storm surge propagation induced by Typhoon Haiyan with Coriolis effect.

Snapshots of Storm Surges in the Philippines



Maximum Simulated Storm Tides at Leyte Gulf



2005 Hurricane Katrina in Gulf of Mexico

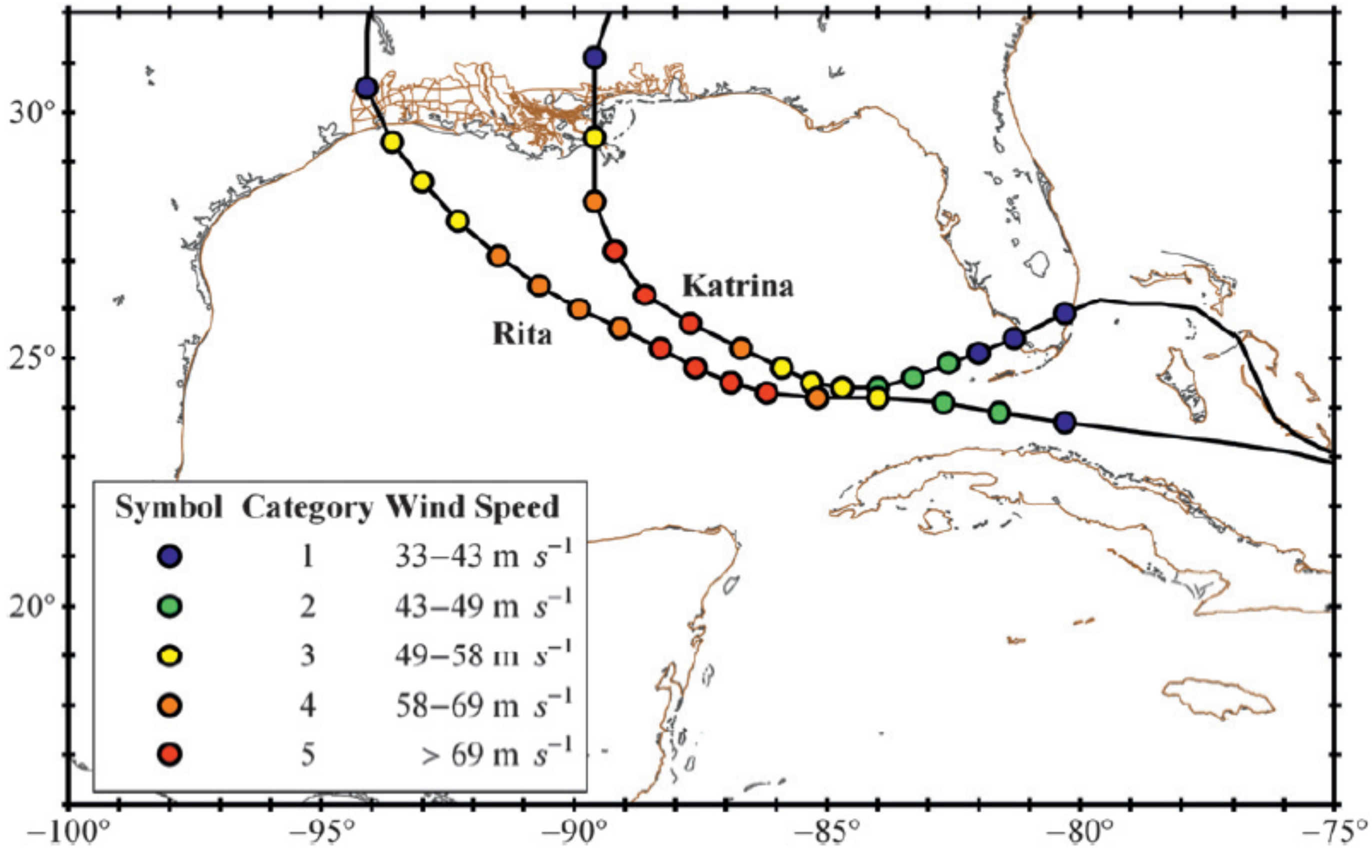
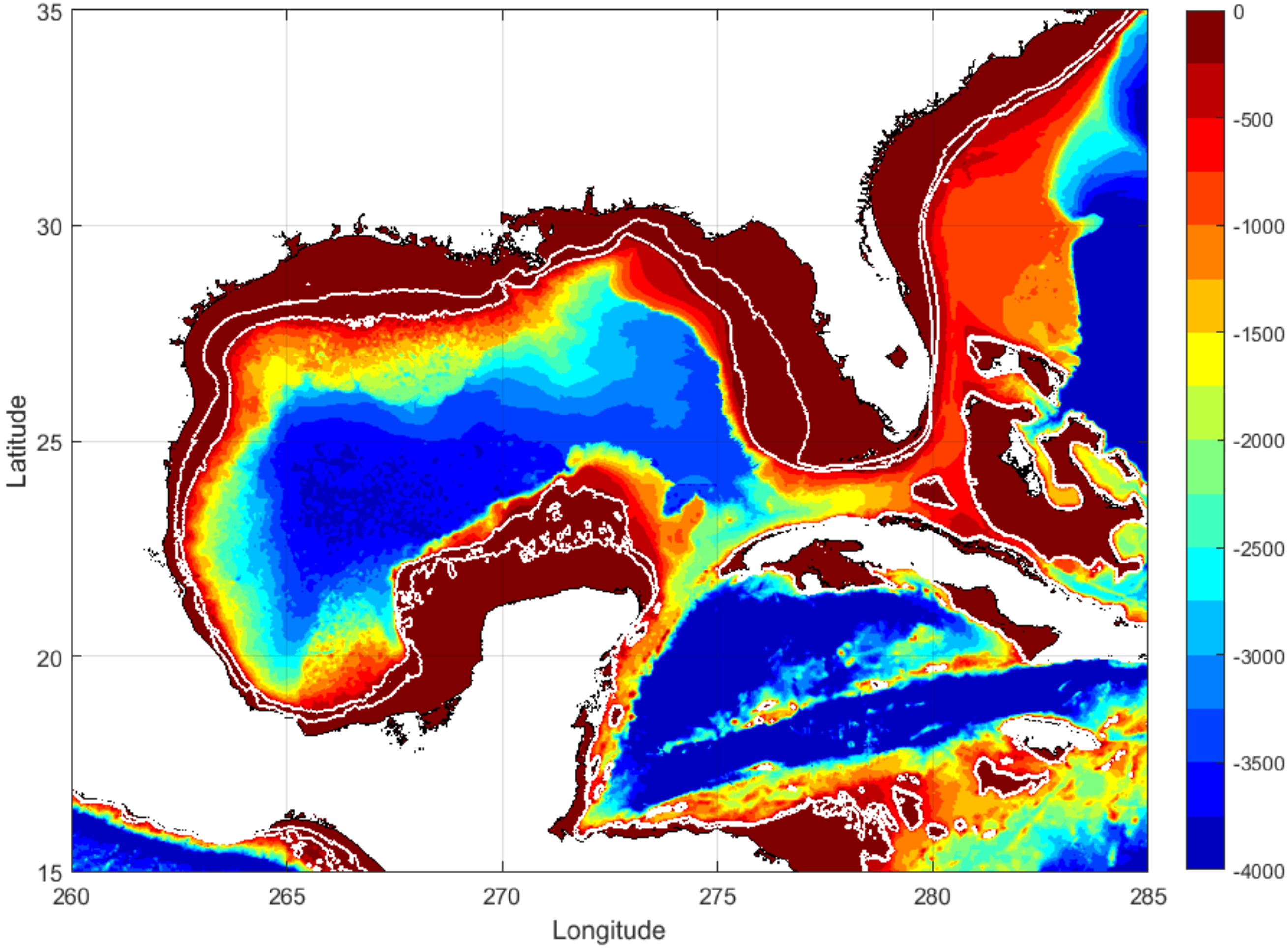


FIG. 1. Storm tracks for Hurricanes Katrina and Rita.

Dietrich et al. (2010)

Computational Domain – Gulf of Mexico

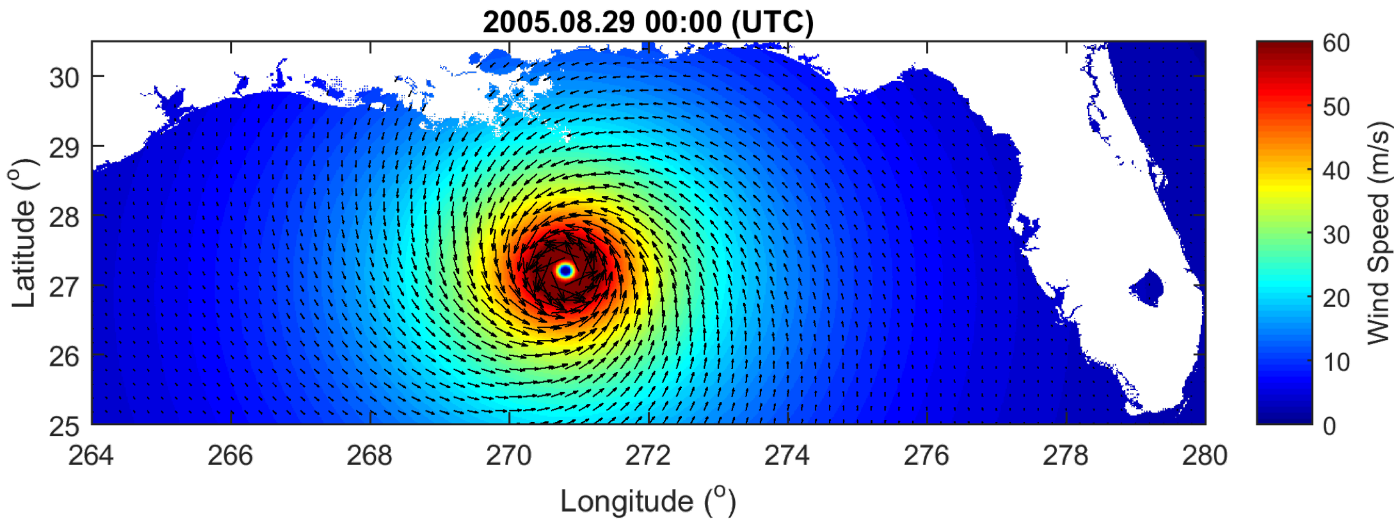


Grid Size = 1 arc-min

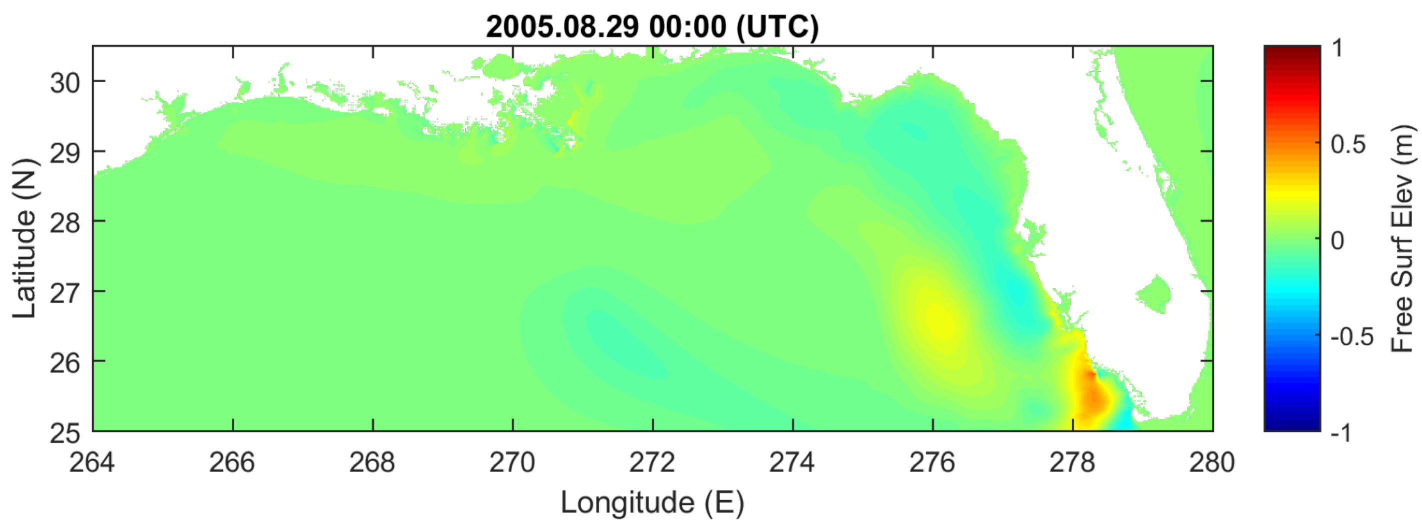
ETOPO1

Katrina Wind-Driven Surge in GoM Coastal Regions

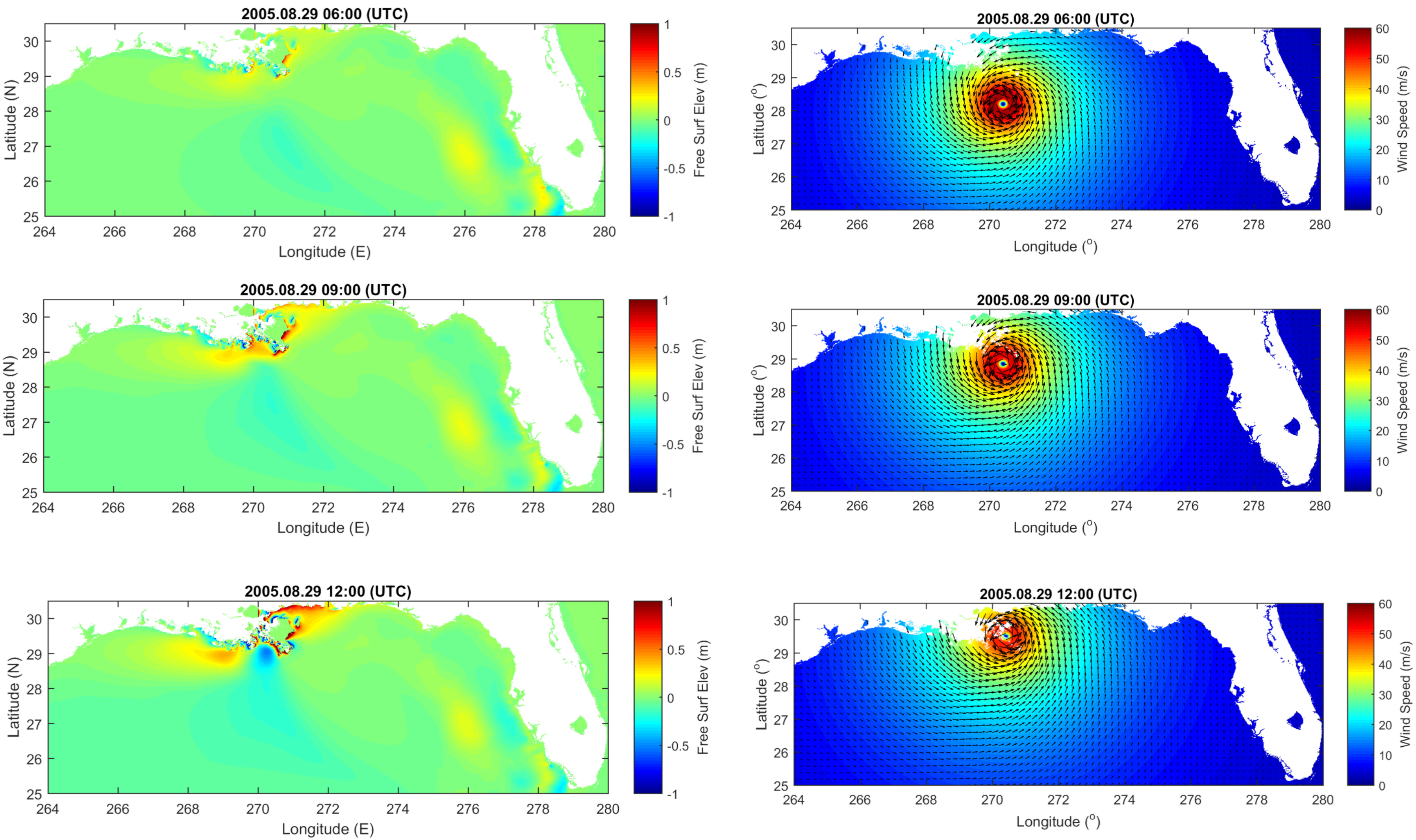
Wind Field



Wind-Driven Surge

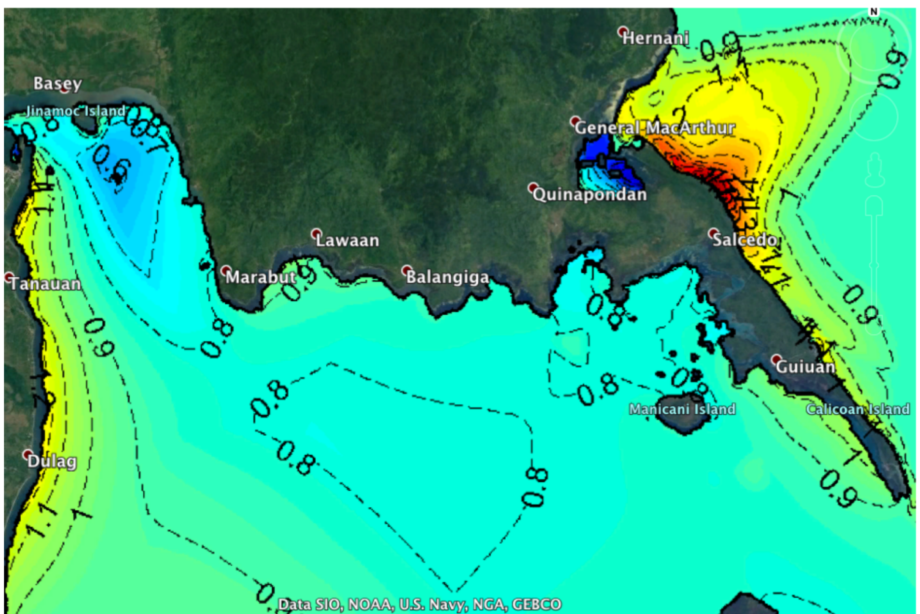


Snapshots of Katrina Wind-Driven Surge



Conclusion

- COMCOT-Surge model can 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**.
- COMCOT-Surge model can combine with the **dynamic atmospheric WRF/ TWRF model and combine** with the **global TPXO tidal model**. The **high-resolution storm surge inundation can be included.**
- COMCOT-Surge model have the high-speed calculation for the **operational system**. It has been the **official** operational system at Central Weather Bureau from 2016.
- Super Typhoon Haiyan in Philippines, Super Typhoon Soudelor in Taiwan, and Category 5 Hurricane Katrina have been studied.



Maximum Simulated Storm Tides at Leyte Gulf, Philippines.

Thanks for your listening.

Welcome for comments and questions.

Yu-Lin Tsai
opo1208@hotmail.com

Prof. Tso-Ren Wu
tsoren@cc.ncu.edu.tw