

澎湖縣災害防救深耕第2期計畫-教育訓練課程(九)

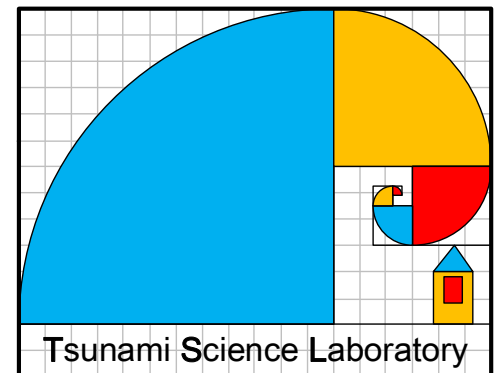
澎湖地區溢淹與暴潮分析(二)

105年09月30日 星期五 10:30 – 11:30

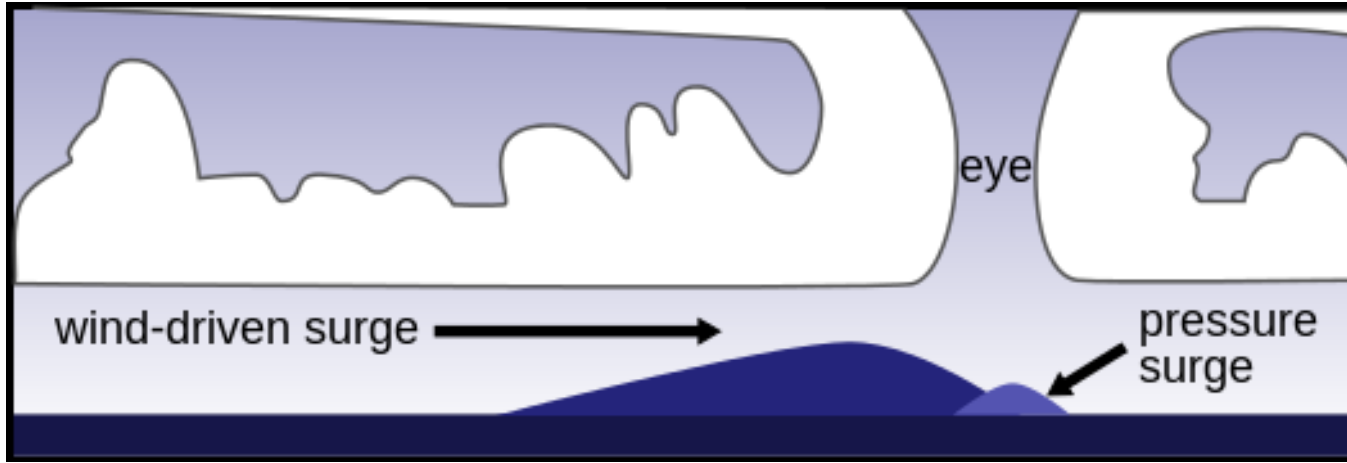
澎湖縣政府消防局4樓簡報室

吳祚任所長、蔡育霖

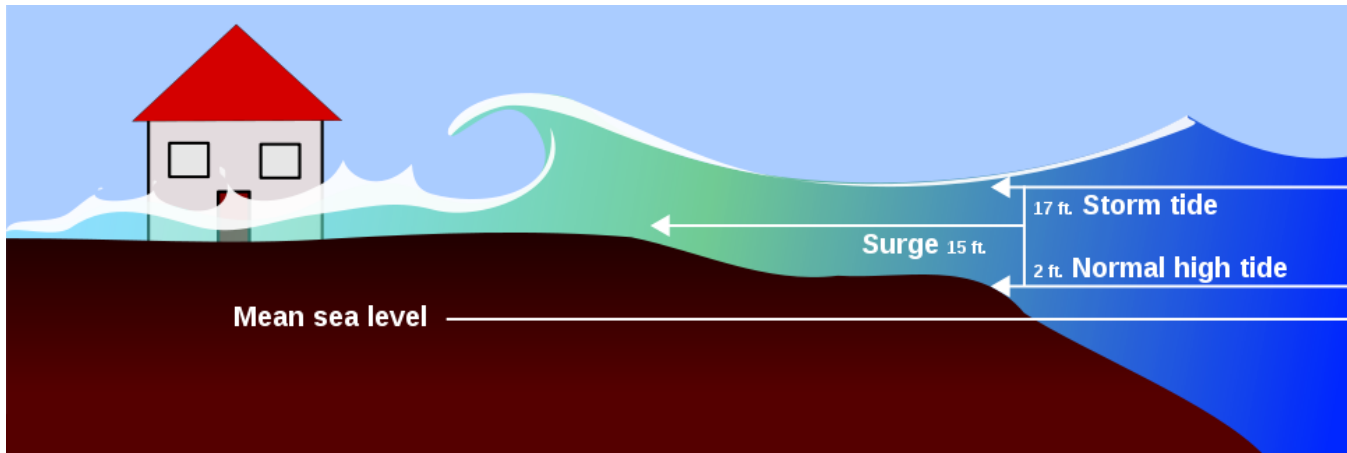
國立中央大學 水文與海洋科學研究所



什麼是風暴潮？



颱風所引起之異常海水面升降(Wiki)



若風暴潮在滿潮或漲潮時發生，將會帶來更大的危險(Wiki)

- 風暴潮是由低氣壓系統所引起之異常水位升降，在不同國家或地區對於低氣壓系統有不同的稱呼：
 - 熱帶氣旋 (Tropical Cyclones)
 - 風暴 (Storms)
 - 颱風 (Typhoons)
 - 颶風 (Hurricanes)
- 主要造成風暴潮的兩種氣象力為：
 - 壓力梯度力 (Pressure Gradient)
 - 風剪力 (Wind Shear Stress)

風暴潮所引起的災害

- 橋樑和道路的破壞
- 對沿岸住屋、社區和商業活動區域的潛在威脅
- 溼地或自然生態的破壞

2005年美國-卡崔納颶風



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

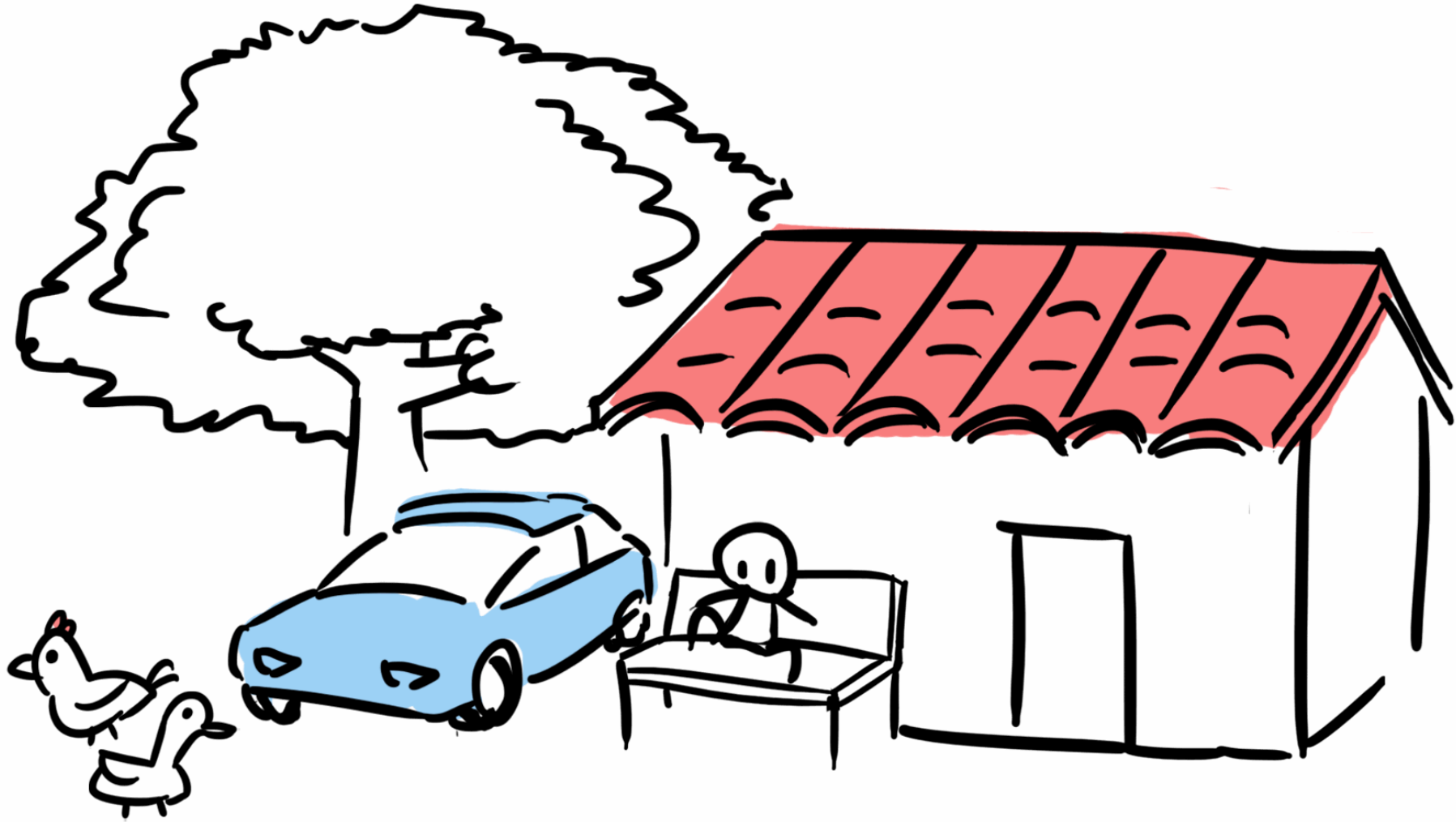
Inundation induced by 2005 Hurricane Katrina.
(<http://www.stormsurge.noaa.gov/>)

2012年美國-珊迪颶風

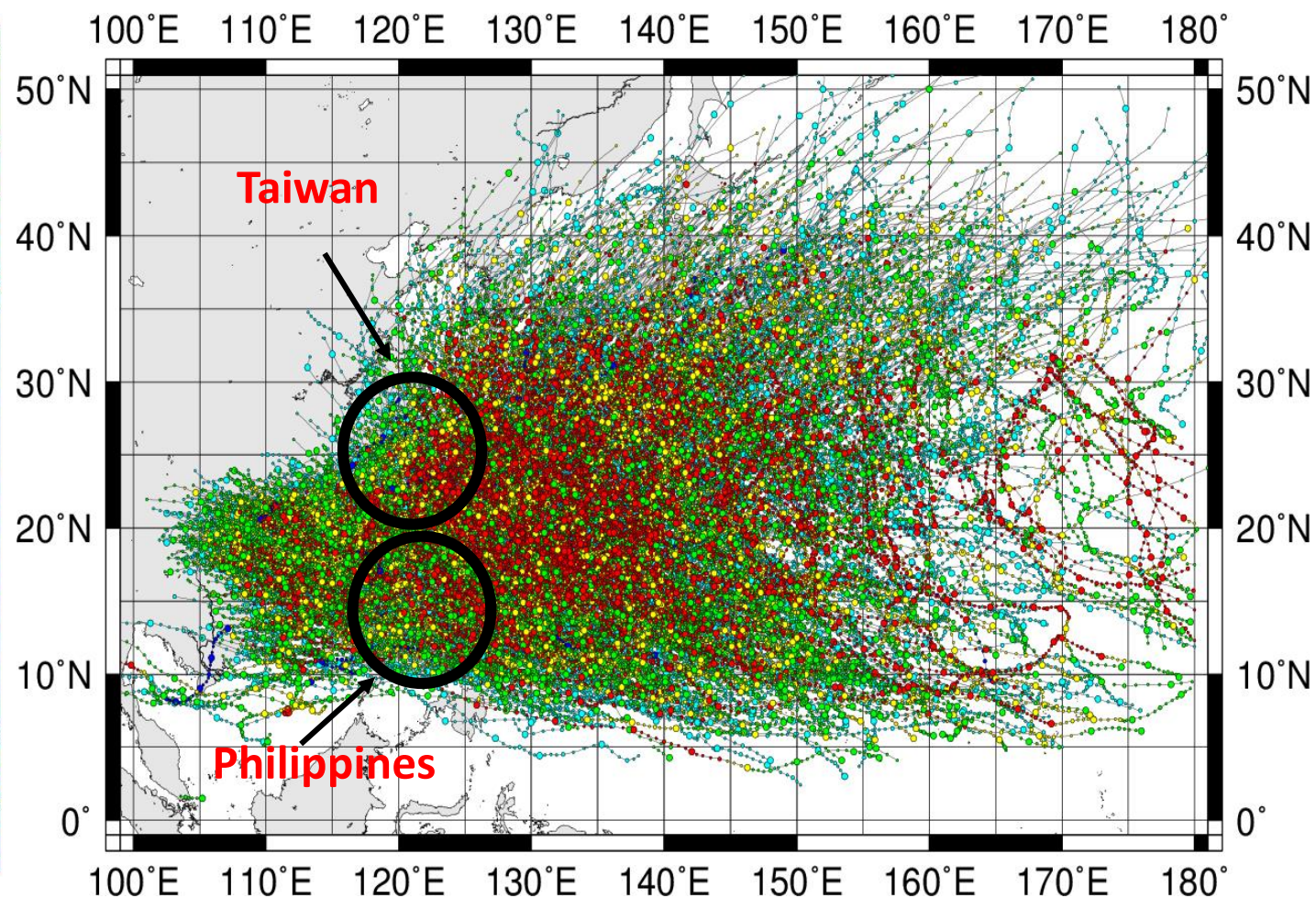
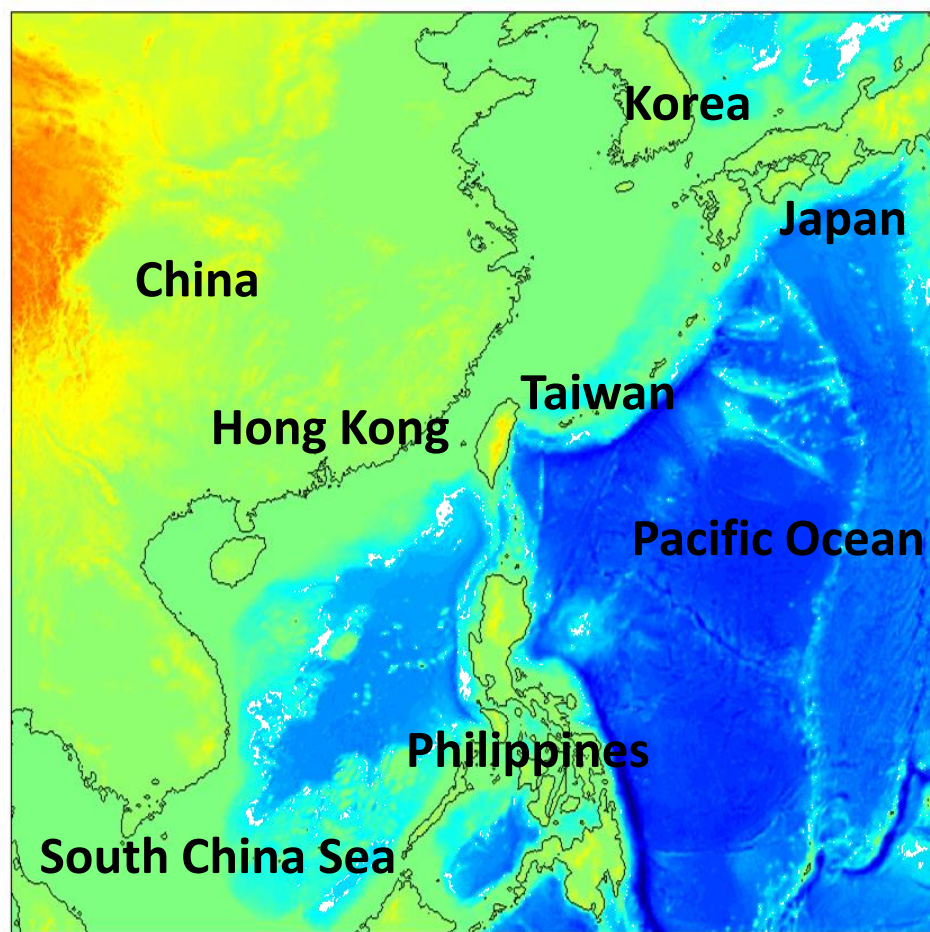


<http://blogs.ei.columbia.edu/2012/10/29/science-behind-sandy/>

風暴潮於近岸地區之溢淹影響(示意圖)



臺灣位處於全球颱風密集最高之區域



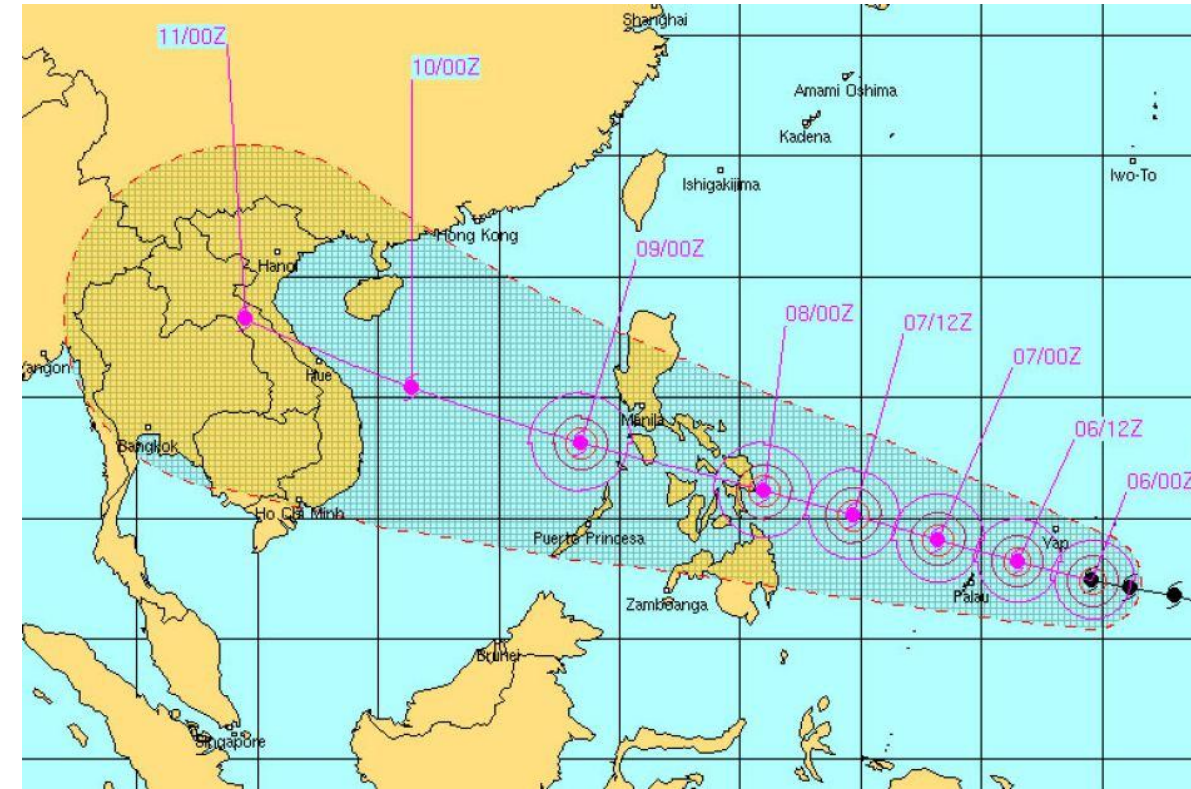
1951年至2014年間，西北太平洋(Northwestern Pacific Ocean)所累積的颱風路徑。

菲律賓-2013年強烈颱風海燕

Typhoon Life Cycle: November 3rd –November 11th

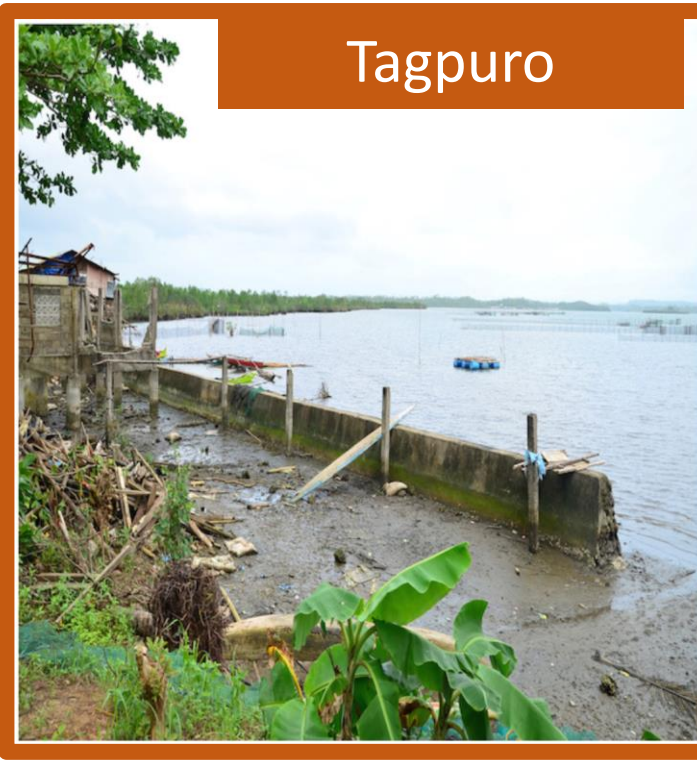
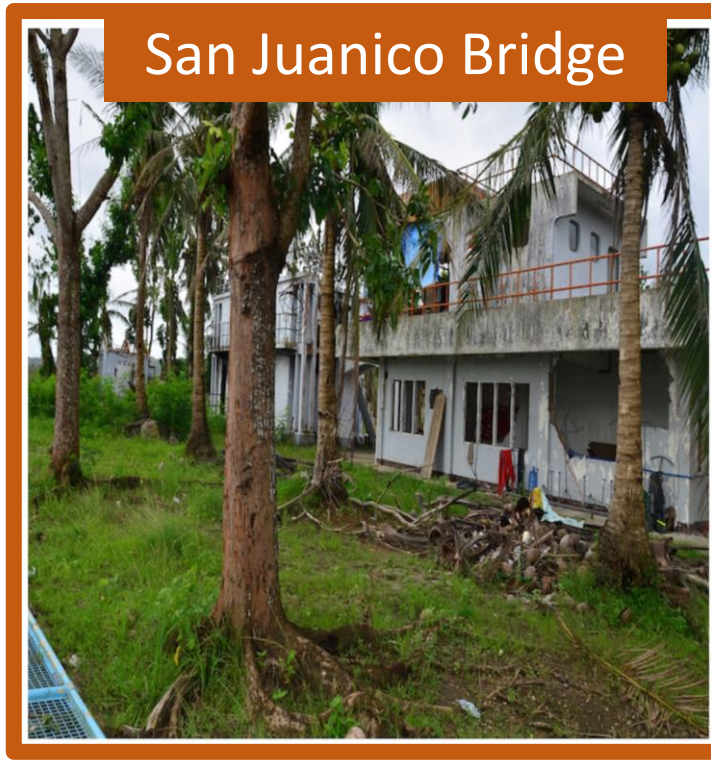


報章雜誌形容，海燕颱風所造成的災情，如世界末日一般。
Typhoon Haiyan: **'It was like the end of the world'.**



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

菲律賓-海燕颱風過後

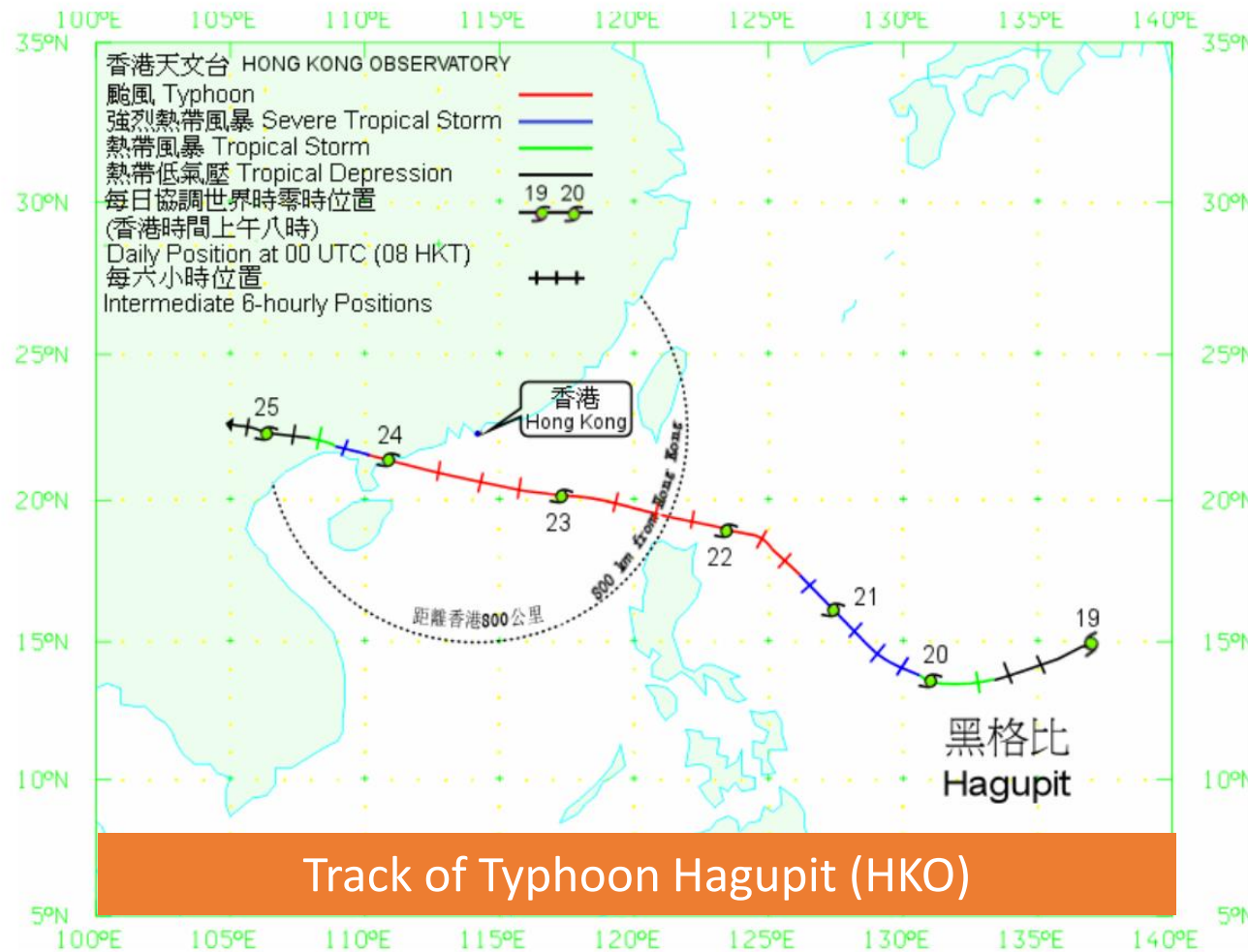


- 1) Inundation height was measured at **5.9 m** near the San Juanico Bridge.
- 2) Sea wall damage at Tagpuro and the run-up height was about **6.9 m**.
- 3) Barangay Rosal area with a **5.0 m** storm surge inundation and damage to houses behind the 3.0 m sea wall.

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

香港-強烈颱風黑格比

2008.09.19 – 2008.09.25



Hong Kong Local News



Saltwater Intrusion



香港維多利亞港所記錄的風暴潮



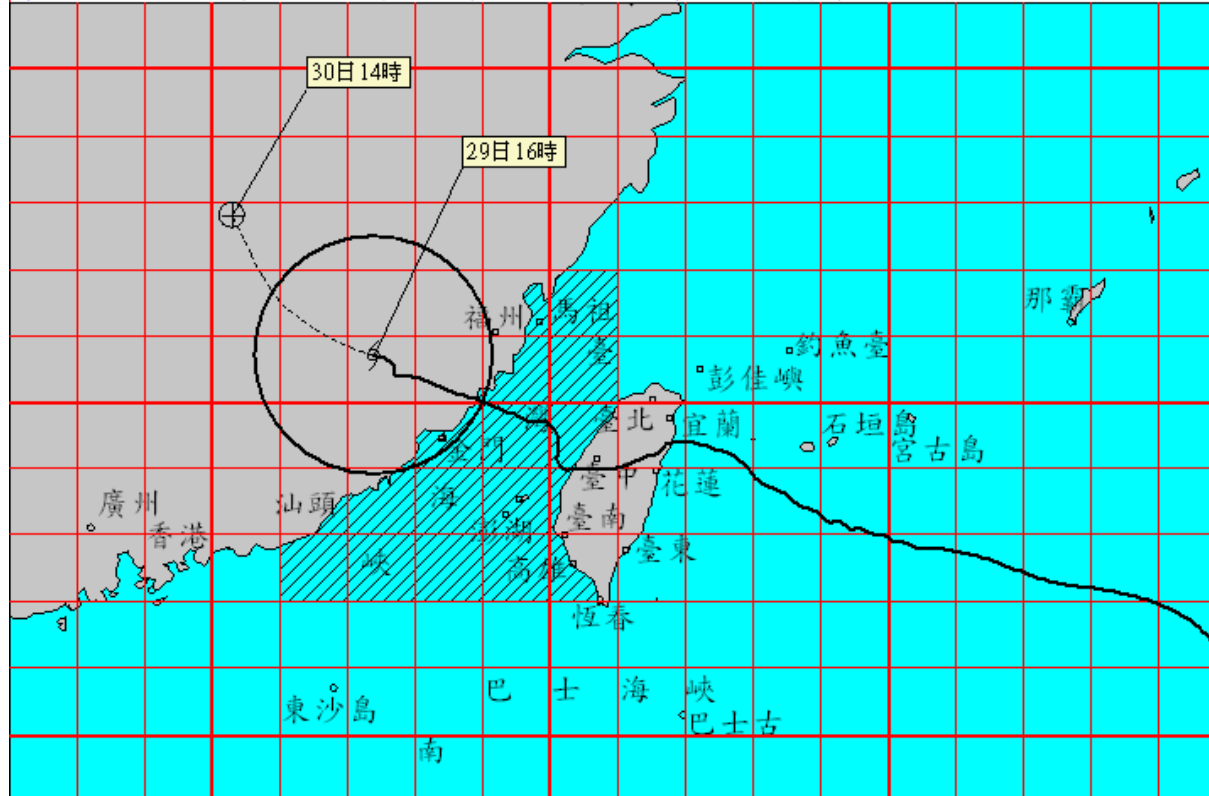
香港天文台 (Hong Kong Observatory)

http://www.weather.gov.hk/m/article_uc.htm?title=ele_00184

臺灣－強烈颱風杜鵑

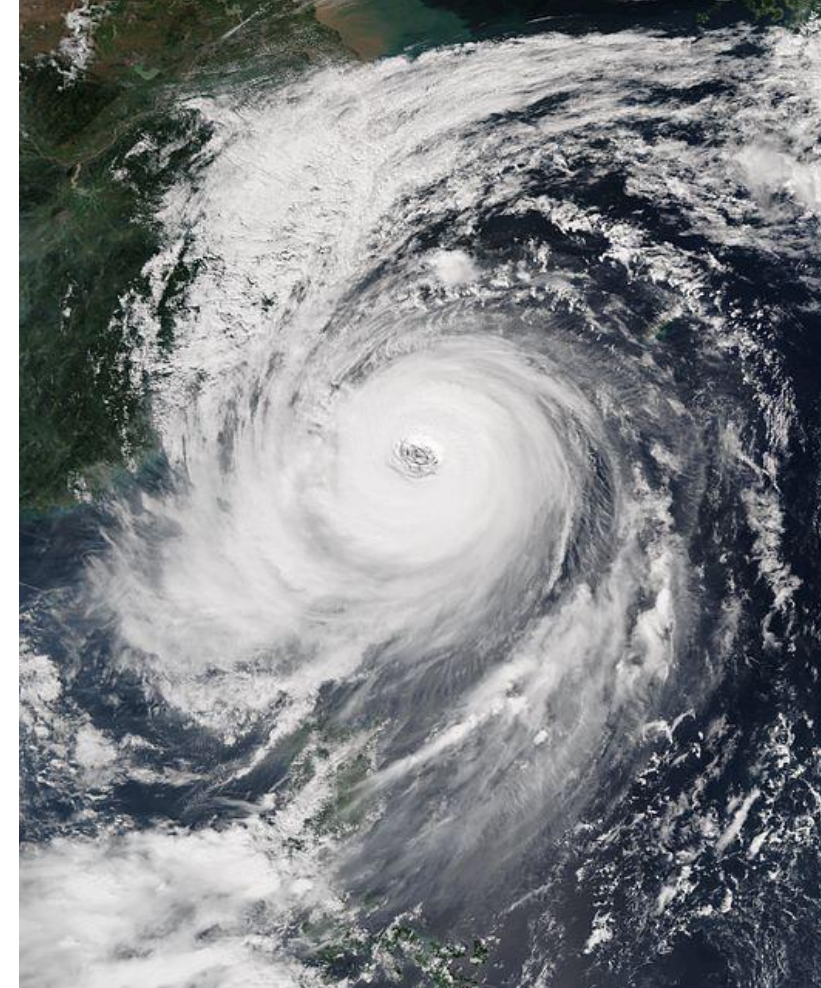
2015.09.15 – 2015.09.29

輕度颱風（編號第21號 國際命名：DUJUAN，中文譯名：杜鵑）
第 19-2 報 民國 104 年 9 月 29 日 16 時 15 分發布



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

Satellite Image

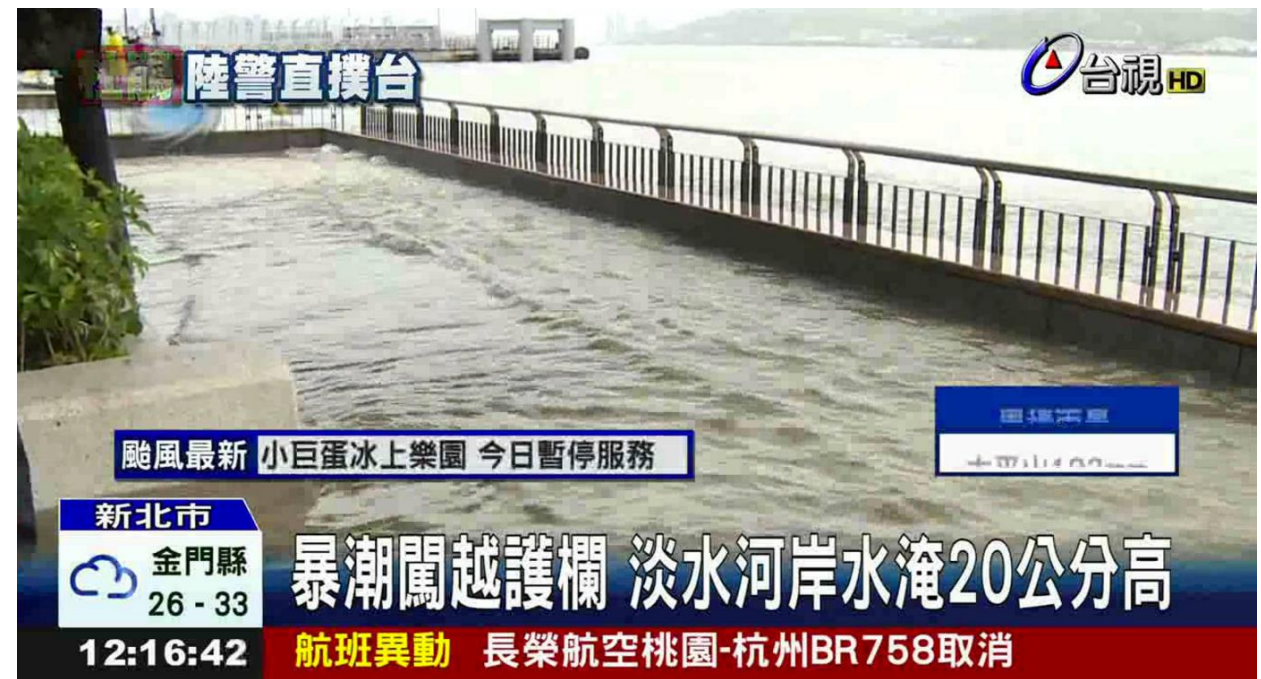


杜鵑颱風之風暴潮引起的 溢淹和海水倒灌



Copyright@UDN News

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



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臺灣歷史上的災難性風暴潮

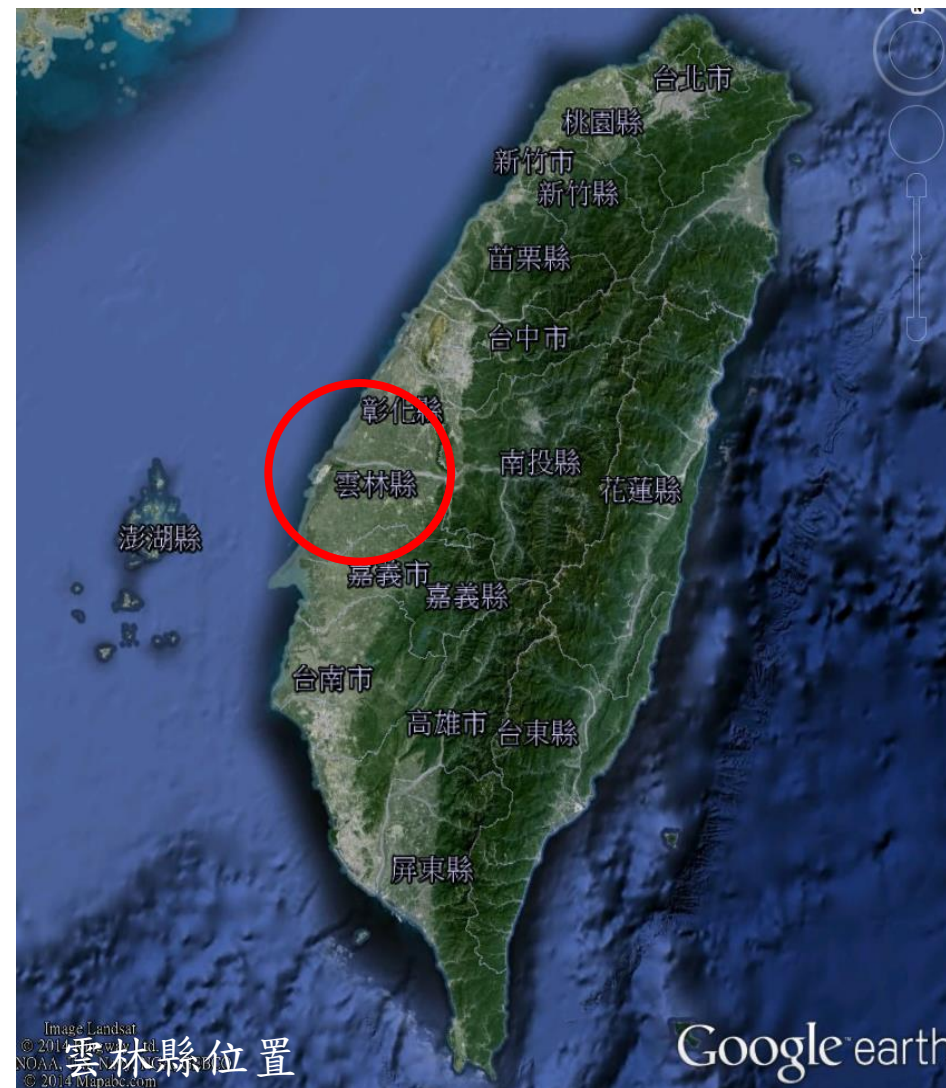
1845年雲林口湖暴潮事件

- 西元1845年（清道光25年）農曆6月7日，連宵大雨，颶風由西南捲向東北，引起海水倒灌，海浪吞沒之沿海九座村莊，分別為下湖街、新港莊、箔仔寮、蚶仔寮、竹苗寮、蝦仔寮、竹達寮等，其中又以竹苗寮、蝦仔寮（今湖口村南、北港溪畔）以及竹達寮（今廣溝厝西南處）等地區災情最為嚴重，俱沒入海中，無一倖存。
- 影響區域遍及雲林沿海一帶，罹難屍首不計其數，最後由朝廷派出官兵前來掩埋，道光皇帝為憐恤百姓，敕封為「萬善同歸」，倖存下來之民眾為告祭先祖，因而有雲林口湖牽水狀告慰冤魂之科教儀式。

（李豐楙，1996；曾人口，1978）



臺灣府輿圖纂要 - 嘉義縣輿圖



雲林縣位置

雲林口湖野外調查

時間：2014.04.29 – 2014.04.30

感謝李俊叡、李宇弘、李珮瑜同學協助



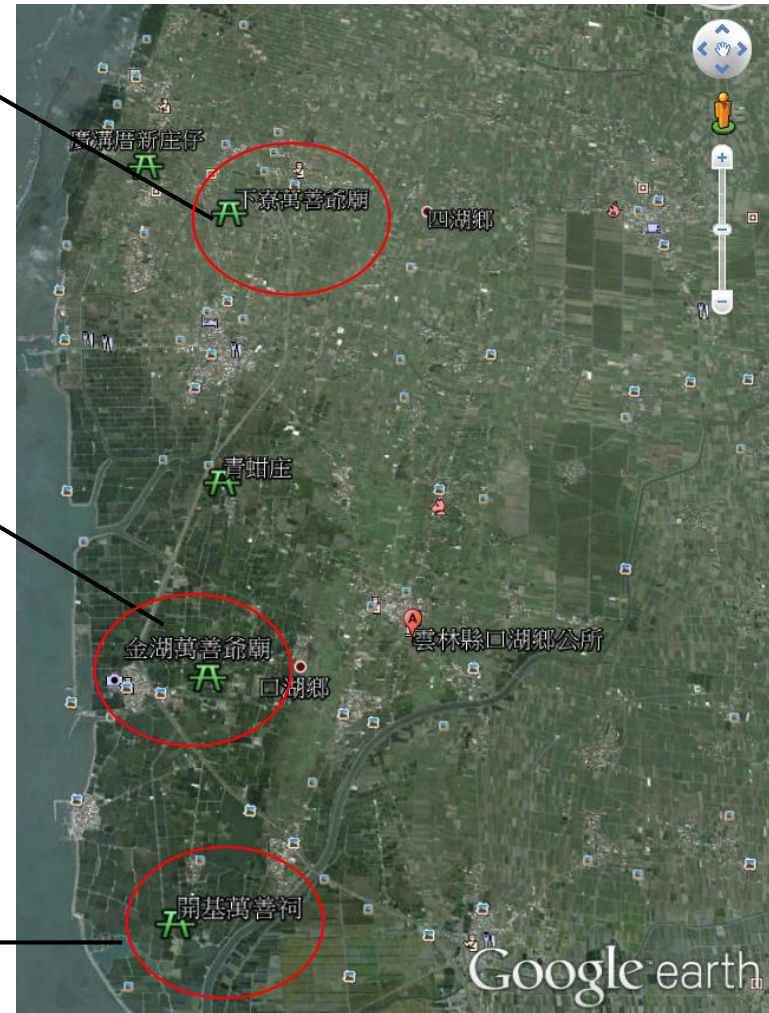
下寮萬善爺廟



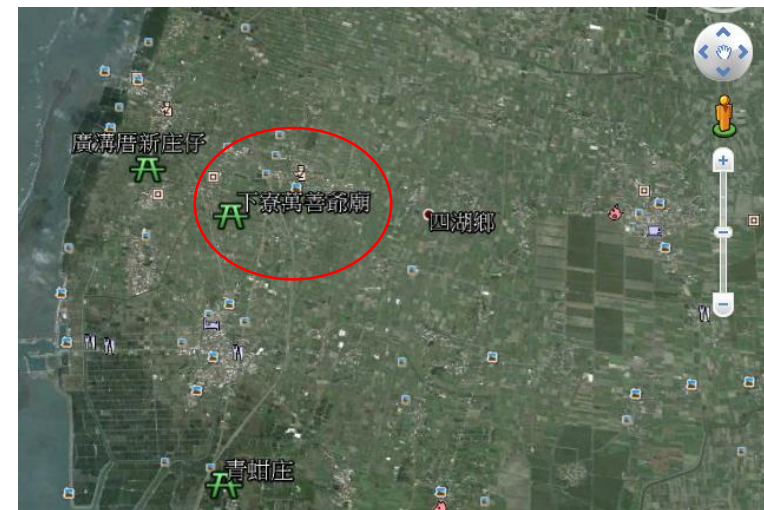
金湖萬善爺廟



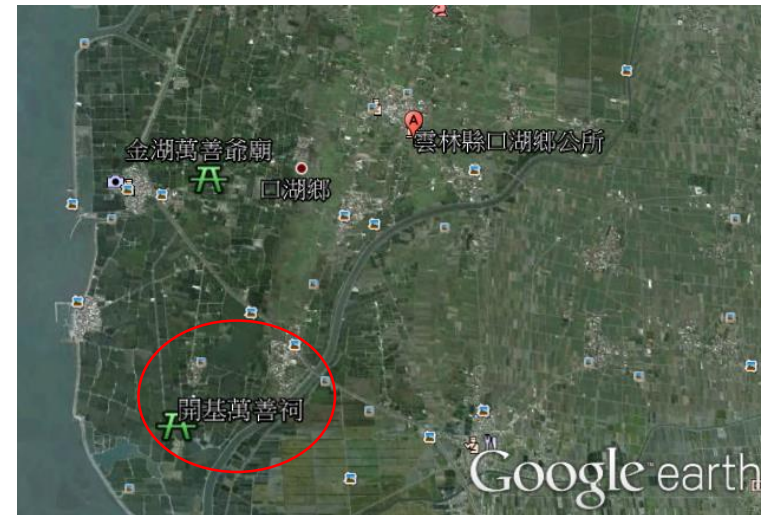
開基萬善祠



下寮萬善爺廟

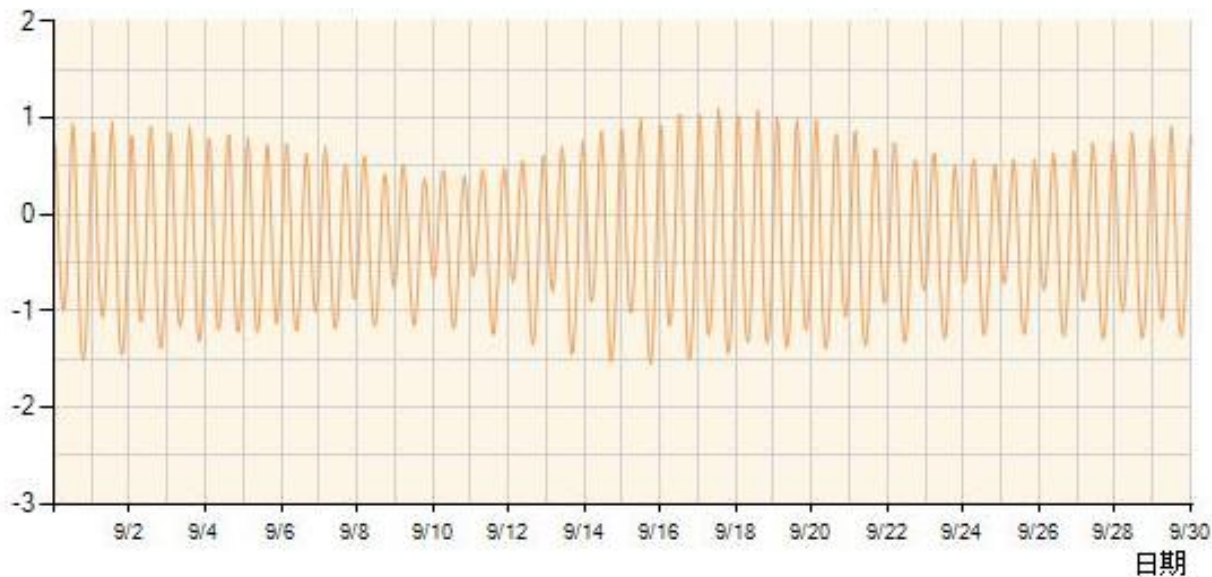


開基萬善祠

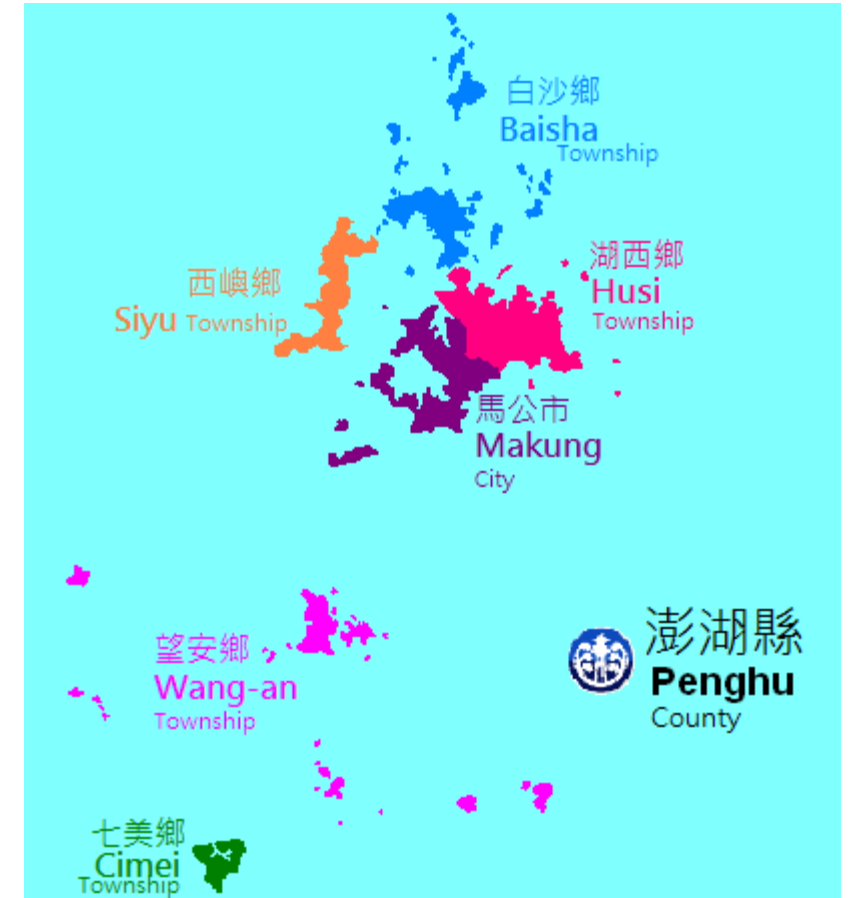


澎湖縣地理環境與自然條件

- 澎湖群島，東距臺灣本島約50公里，西離歐亞大陸約140公里，由90個大小島嶼組成，總面積約為126.864平方公里。
- 澎湖群島根據調查，東至查母嶼，西至花嶼，南及七美嶼，北及大蹺嶼，而北回歸線穿過群島之中的虎井嶼南方(澎湖縣政府官方資料)。



中央氣象局公佈澎湖馬公港的潮汐預報資料，潮差可達2.5公尺以上。



澎湖島嶼眾多

澎湖潛在的暴潮危害

2014.10.09 19:38 蘋果新聞

全球暖化海平面上升，加上今午適逢**農曆大潮**及颱風低氣壓作祟，導致澎湖縣沿海不少低窪地區都出現**海水倒灌**情形，如**馬公市第二漁港碼頭**，海水都漫到馬路上來，就連位於**白沙鄉港子村澎湖水族館**的停車場與港子國小，都因倒灌的海水源源不斷循著排水系統由水溝蓋湧入成水鄉澤國，水淹數公分高，騎車經過民眾被迫水上行車，就連貓咪也嚇得躲上高牆來回踱步，不知何去何從才好。



白沙鄉港子因為海水回灌，部分低窪區成水鄉澤國。許逸民攝

<http://www.appledaily.com.tw/realtimenews/article/new/20141009/484919/>



CTV NEWS

嚴防恐怖大潮

豪雨、大雨警戒區

台南市、高雄市

強颱 杜鵑

週三

週二

現在

澎湖縣

晚間停班課

中視新聞 f

強颱杜鵑鬧中秋 澎湖馬公港暴潮淹水

強颱來襲

國泰醫院 今急診照常 開放部分門診.夜診停診

澎湖過去的暴潮案例-2015年杜鵑颱風

強颱杜鵑來襲，又逢農曆16日**天文最大潮**，澎湖今天近午11許正逢滿潮，海水倒灌淹過馬公漁港碼頭道路，比較低窪的白沙鄉赤崁村，甚至還淹到地面數公分，成為水鄉澤國。幸好，風雨還不大，並未傳出重大災情。

包括馬公商港、第二漁港和第三漁港，都可見海水與碼頭面平齊的難得景象，甚至海水還越過碼頭漫上道路，駕駛一經過，就仿如陸上行舟。而不少滯留旅客，也苦中作樂，到此觀看難得**暴潮**景象。

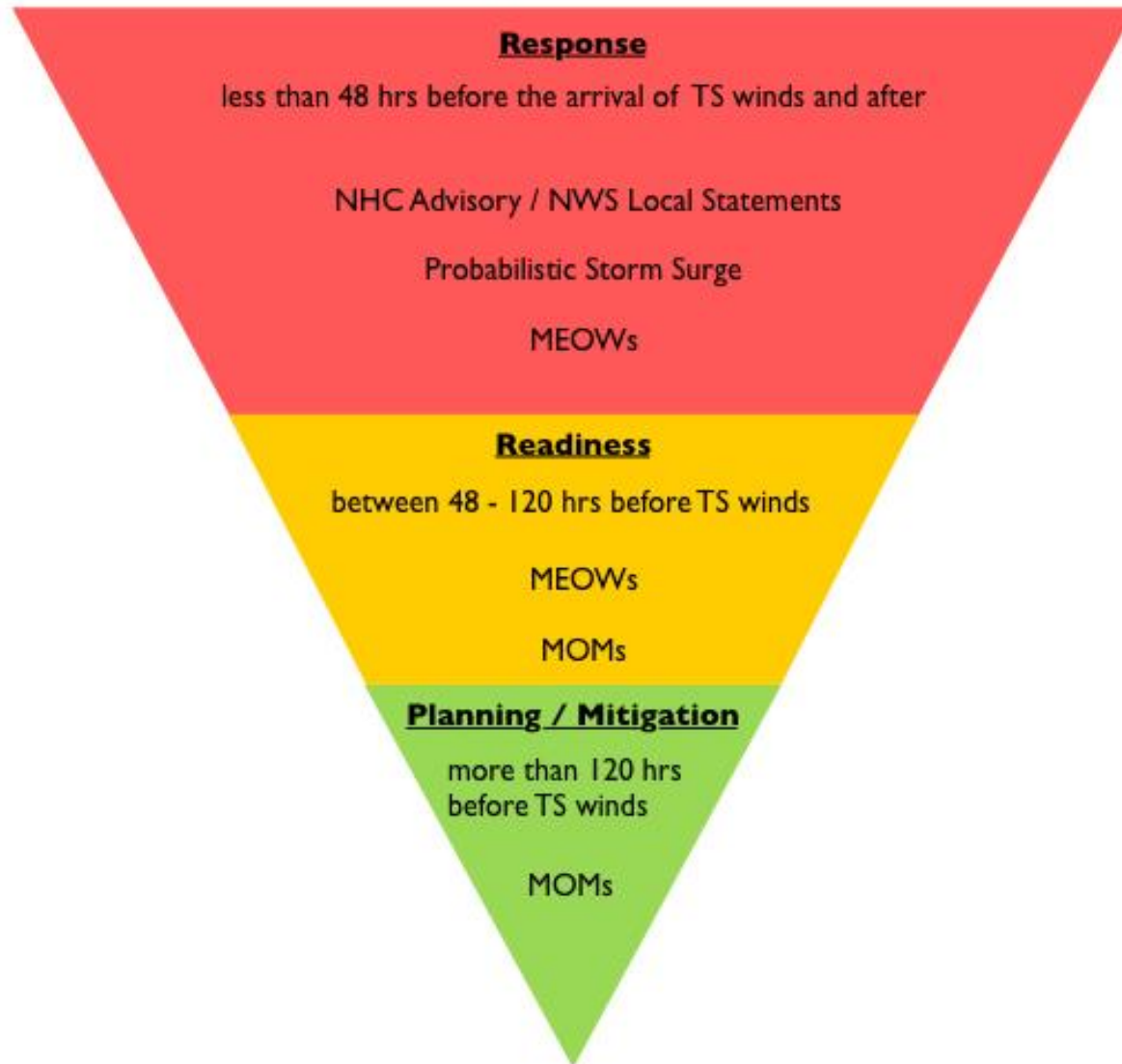


馬公商港碼頭也難抵暴潮，潮水面淹上馬路。許逸民攝



海水淹上碼頭，就連馬公第二漁港漁船加油站也難倖免，漁民涉水加油。許逸民攝

因應風暴潮災害之不同階段(以美國為例)



颶風來臨前之120小時：
規畫與減災 (Planning/ Mitigation)

颶風來臨前之48小時－120小時：
準備 (Readiness)

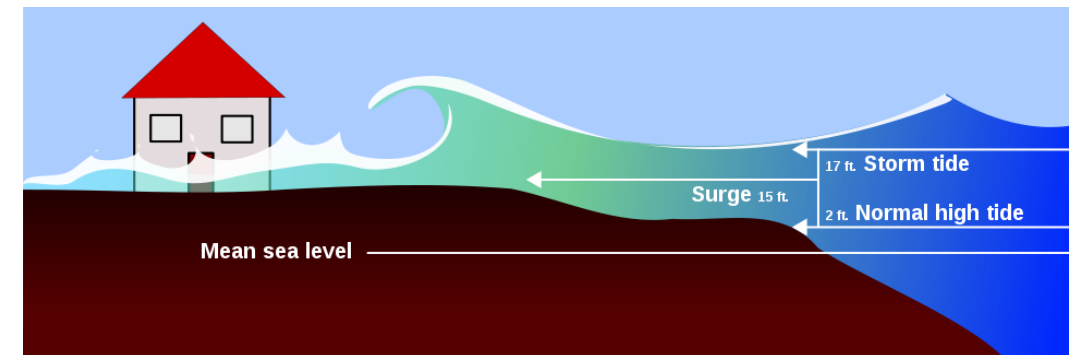
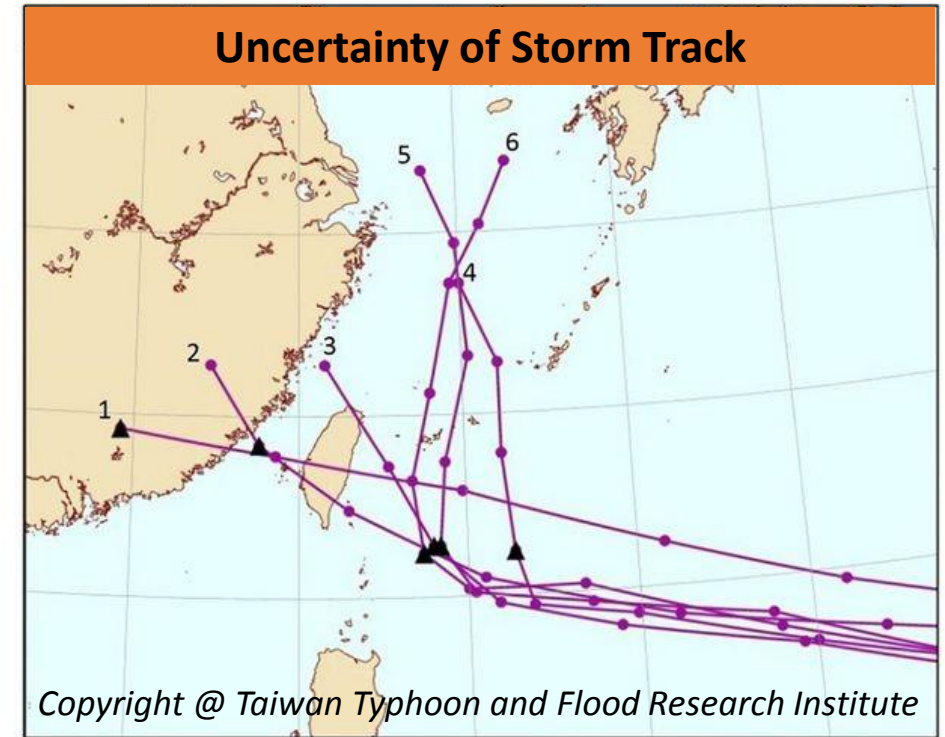
颶風來臨前之48小時內：
因應 (Response)



需要一套精準、計算快速且可作
業化之風暴潮模式。

風暴潮作業模式之目標與要求

- 採球座標系統之尺度計算域，完整涵蓋颱風生命週期和風暴潮傳遞。
- 計算過程包含：近岸區域且不同尺度風暴潮下之非線性效應、底床摩擦以及淺化作用。
- 計算高解析度的溢淹範圍。
- 與大氣動力模式和天文潮模式之結合。
- 模式可進行高效能之計算並符合預報時效。



Tidal Effect with Storm Surges (Wiki)

COMCOT風暴潮溢淹預報模式之介紹 (Cornell Multi-grid Coupled Tsunami Model – Storm Surge)

Nonlinear Shallow Water Equations on the Spherical Coordinate

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

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

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

- 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.

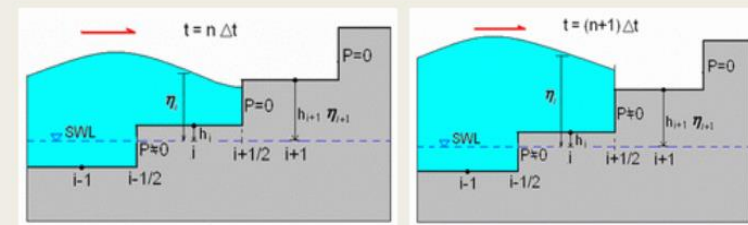


Fig.02 Moving Boundary Scheme

(1). 溢淹計算之國際基準案例比對

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

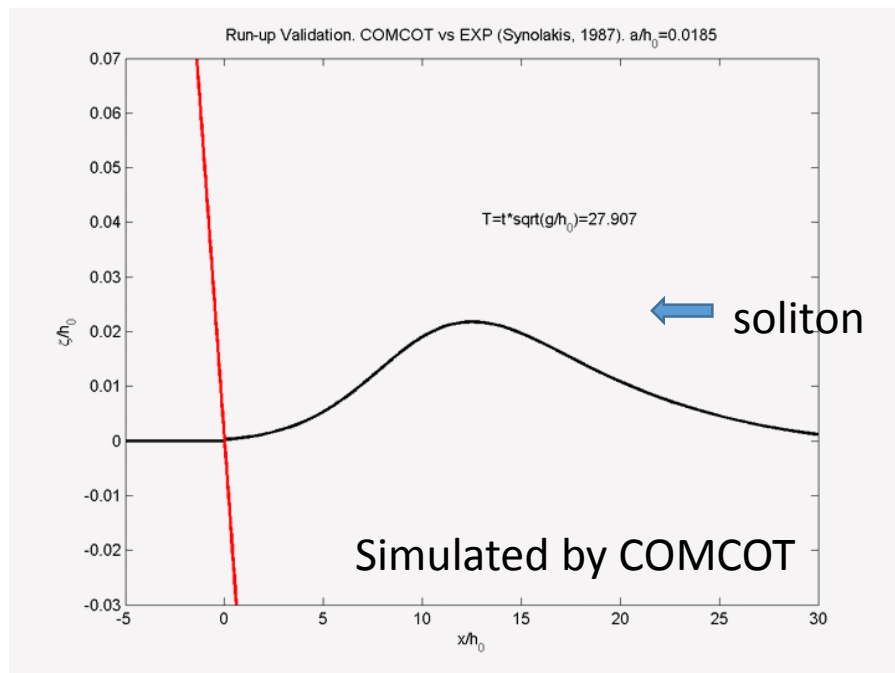
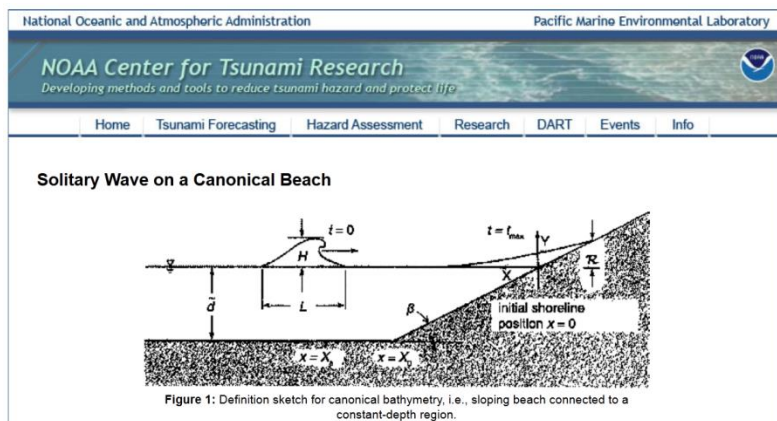
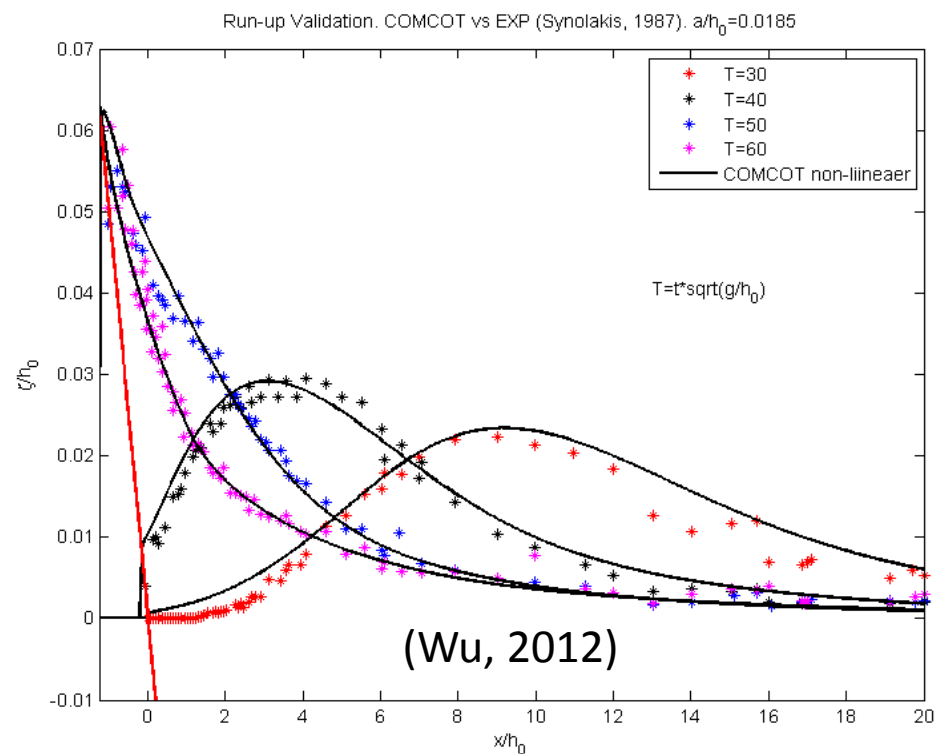


Figure 2: Time evolution of $H = 0.0185$ initial wave over a sloping beach with $\cot \beta = 19.85$ from $t = 25$ to 65 with 10 increments. Constant depth-segment starts at $X_0 = 19.85$. While markers show experimental results of Synolakis (1986, 1987), solid lines show nonlinear analytical solution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

(from NOAA Official Website)

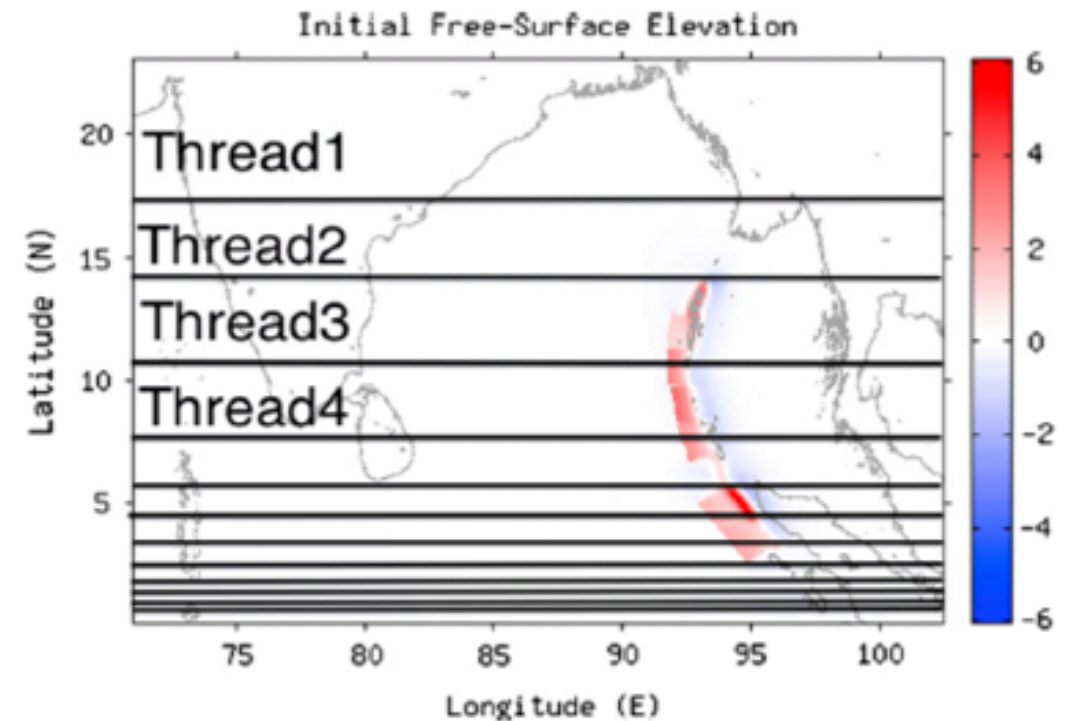
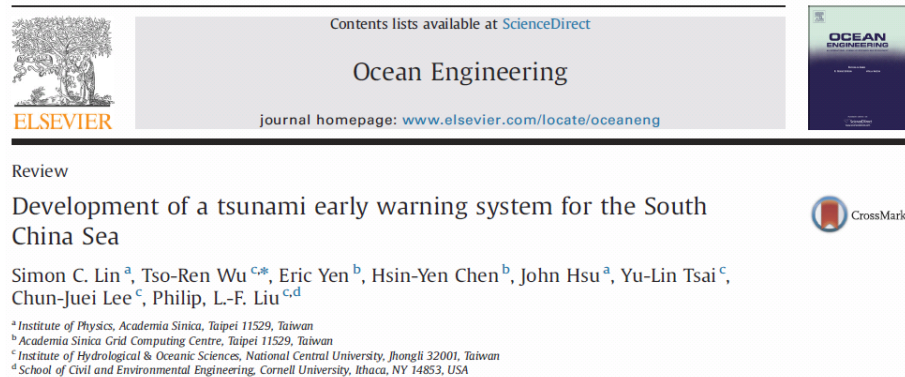


(2). 高效能之數值計算

Our model can finish 48 hrs forecast in 1 hours and be used for the operational system.

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

Parallel Computing on Multi Cores.



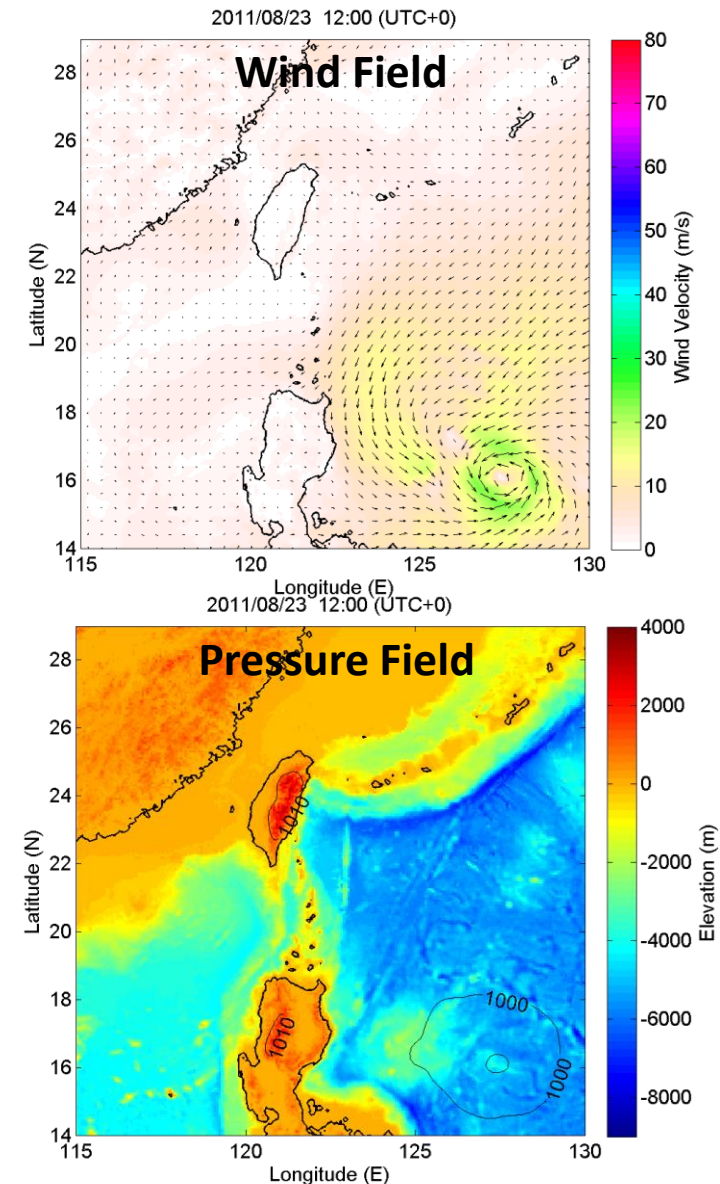
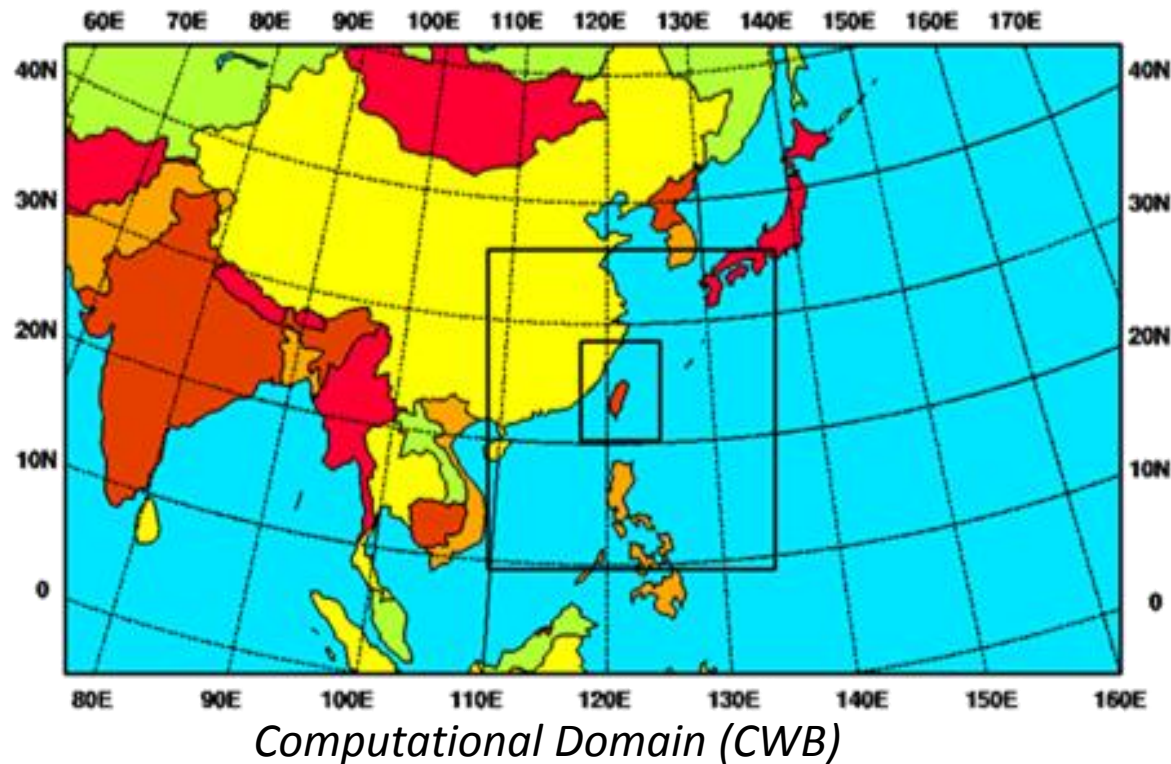
Dynamic resources sharing.

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

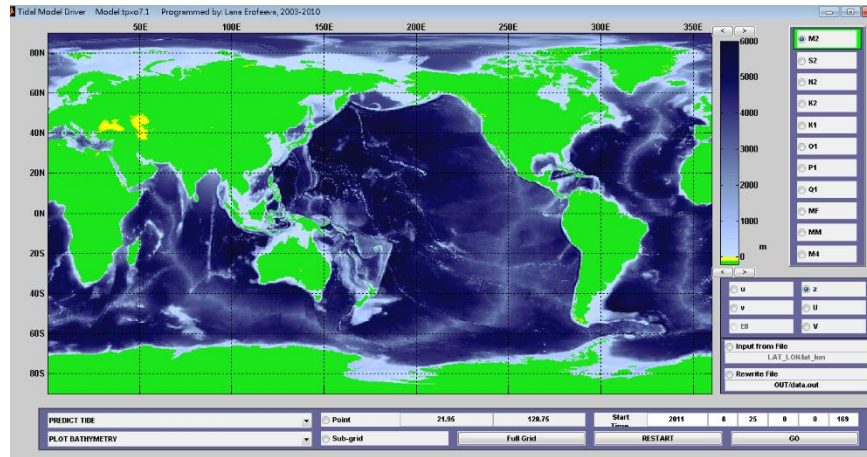
(3). 與國際知名大氣動力模式之結合

WRF (Weather Research and Forecasting Model)

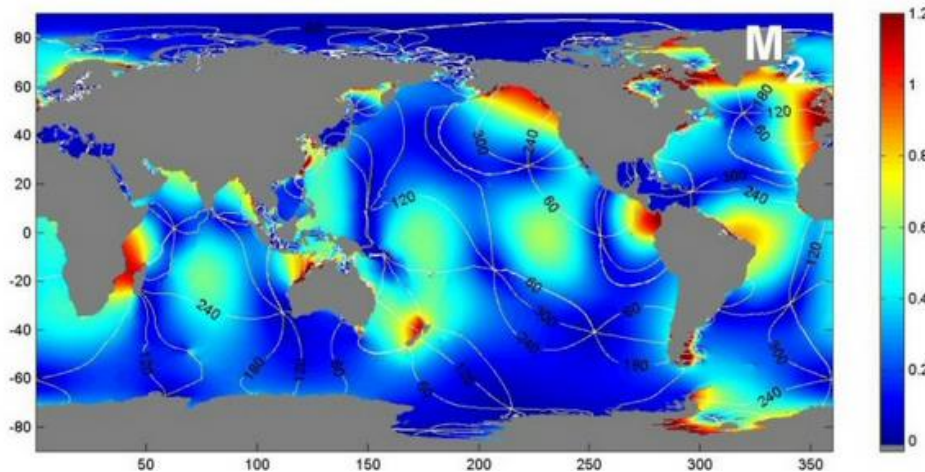
- WRF model is an atmospheric model adopted for operational forecasts by Central Weather Bureau in Taiwan.
- The WRF model will start its simulation per 6 hours in a day at 00, 06, 12 and 18 UTC time respectively.



(4). 與國際知名之全球天文潮模式結合 (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

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³Scripps Institution of Oceanography, La Jolla, CA, U.S.A.

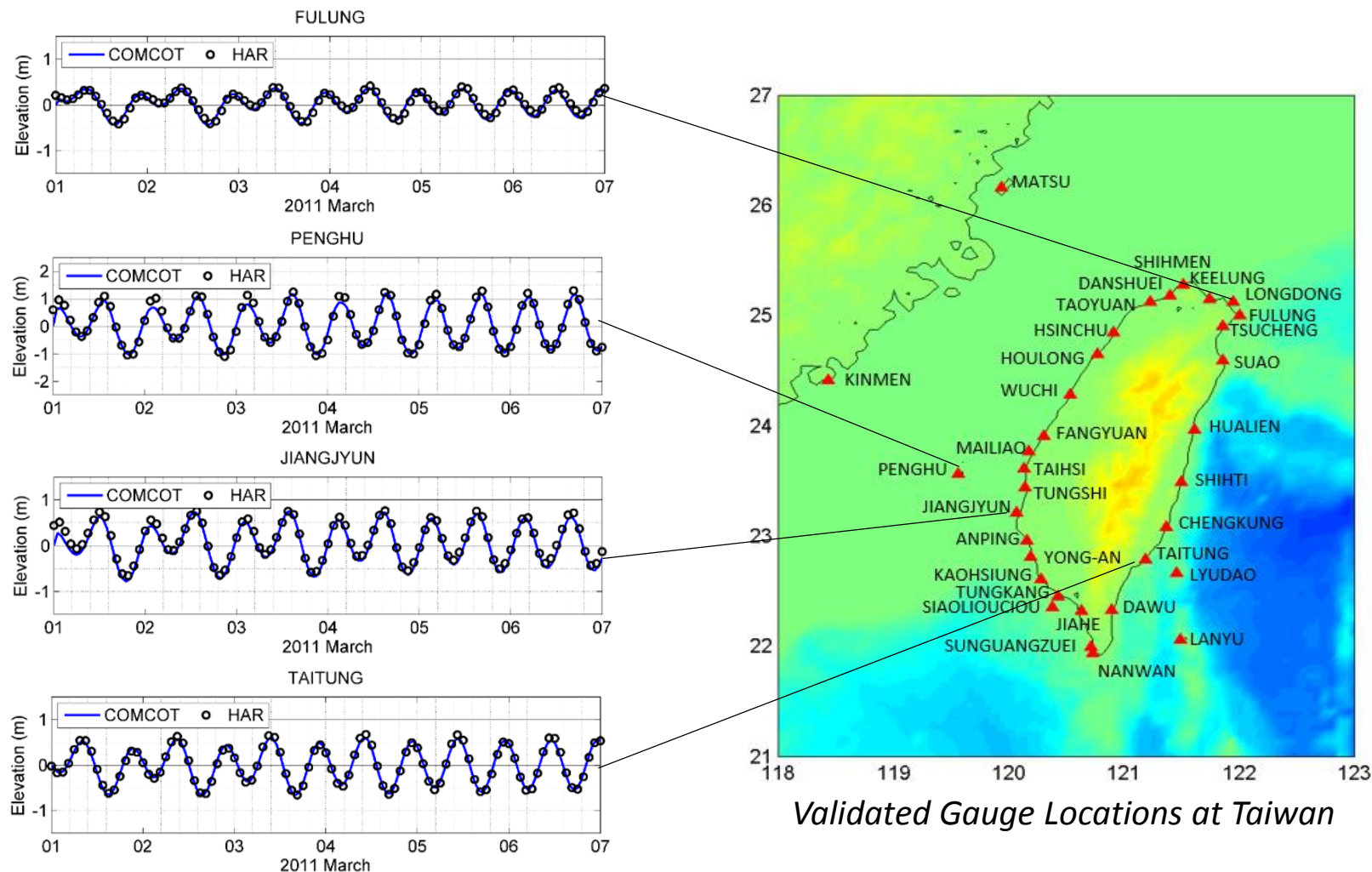
⁴Department of Electrical Engineering and Computer Science, University of Michigan,
Ann Arbor, MI, U.S.A.

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 M₂ tidal vorticity ($3\text{--}8 \times 10^{-9} \text{ s}^{-1}$, $210\text{--}310^\circ$) agree with those derived from the TPXO.2 model ($2\text{--}5 \times 10^{-9} \text{ s}^{-1}$, $250\text{--}300^\circ$), whereas harmonic constants of about ($1\text{--}2 \times 10^{-9} \text{ s}^{-1}$, $350\text{--}360^\circ$) 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. © 1998 Elsevier Science Ltd. All rights reserved

(Dushaw et al., 1997)

(5). 高精準之臺灣區域潮位校驗

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



Validated Gauge Locations at Taiwan

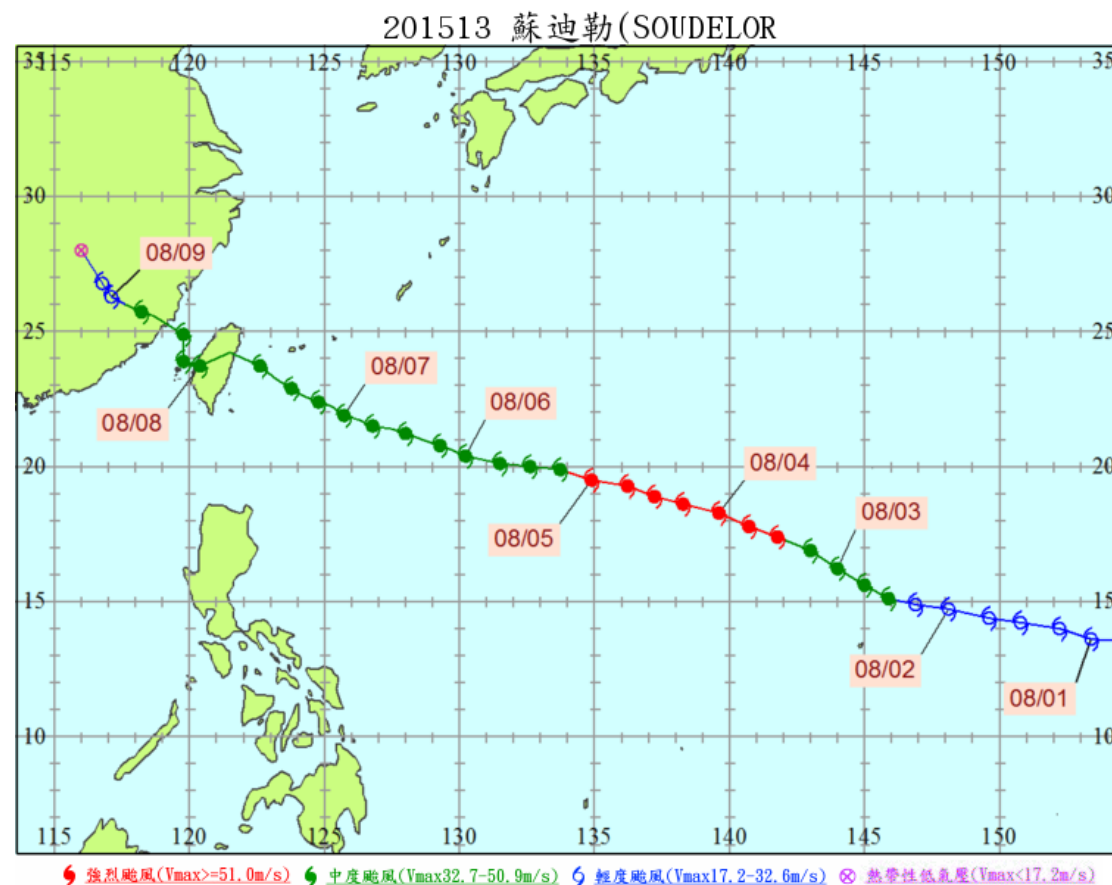
The observed data and harmonic data are provided by CWB (Taiwan).

2015年蘇迪勒颱風案例

- 蘇迪勒為2015年為西北太平洋地區中之強烈颱風，根據初步統計，颱風期間全臺逾400萬戶停電，累計降雨量超過1,000毫米，同時由於蘇迪勒颱風在馬里亞納群島、臺灣和中國大陸均造成嚴重破壞、經濟損失和人員傷亡，因此在第48屆世界氣象組織颱風委員會會議中提議，被永久除名。

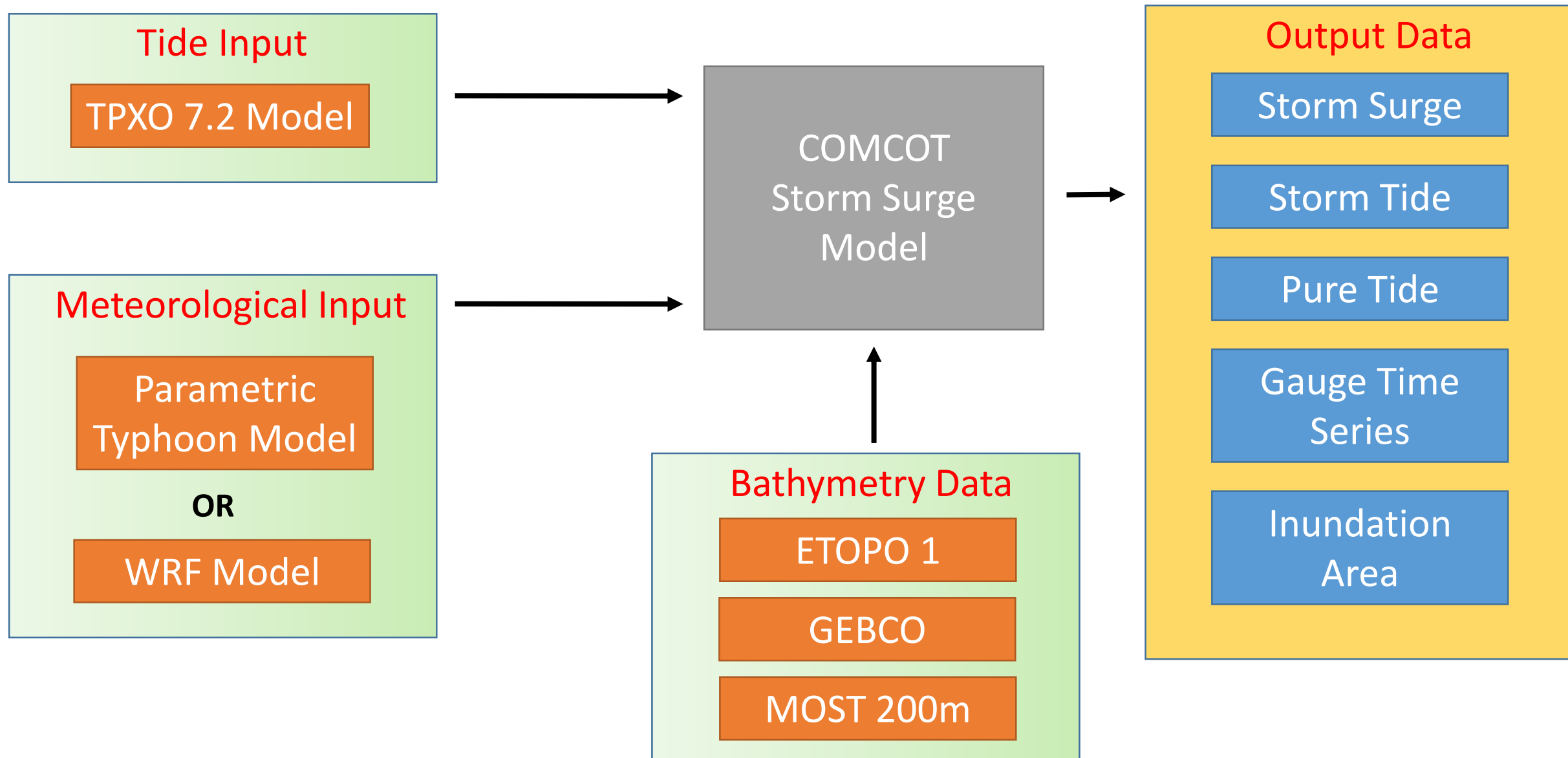


颱風蘇迪勒帶來強風豪雨，宜蘭縣五結鄉部分低窪地區8日淹水，水深及腰(中央社記者沈如峰宜蘭縣)。



(資料來源：中央氣象局颱風資料庫)

蘇迪勒案例分析之流程



參數化颱風模式

Pressure Field

$$P_a = P_c + (P_n - P_c) \exp\left[-\left(\frac{R_{\max}}{r}\right)^B\right]$$

Wind Field

$$V_w = 2 \cdot V_{\max} \cdot \frac{R_{\max} \cdot r}{R_{\max}^2 + r^2}$$

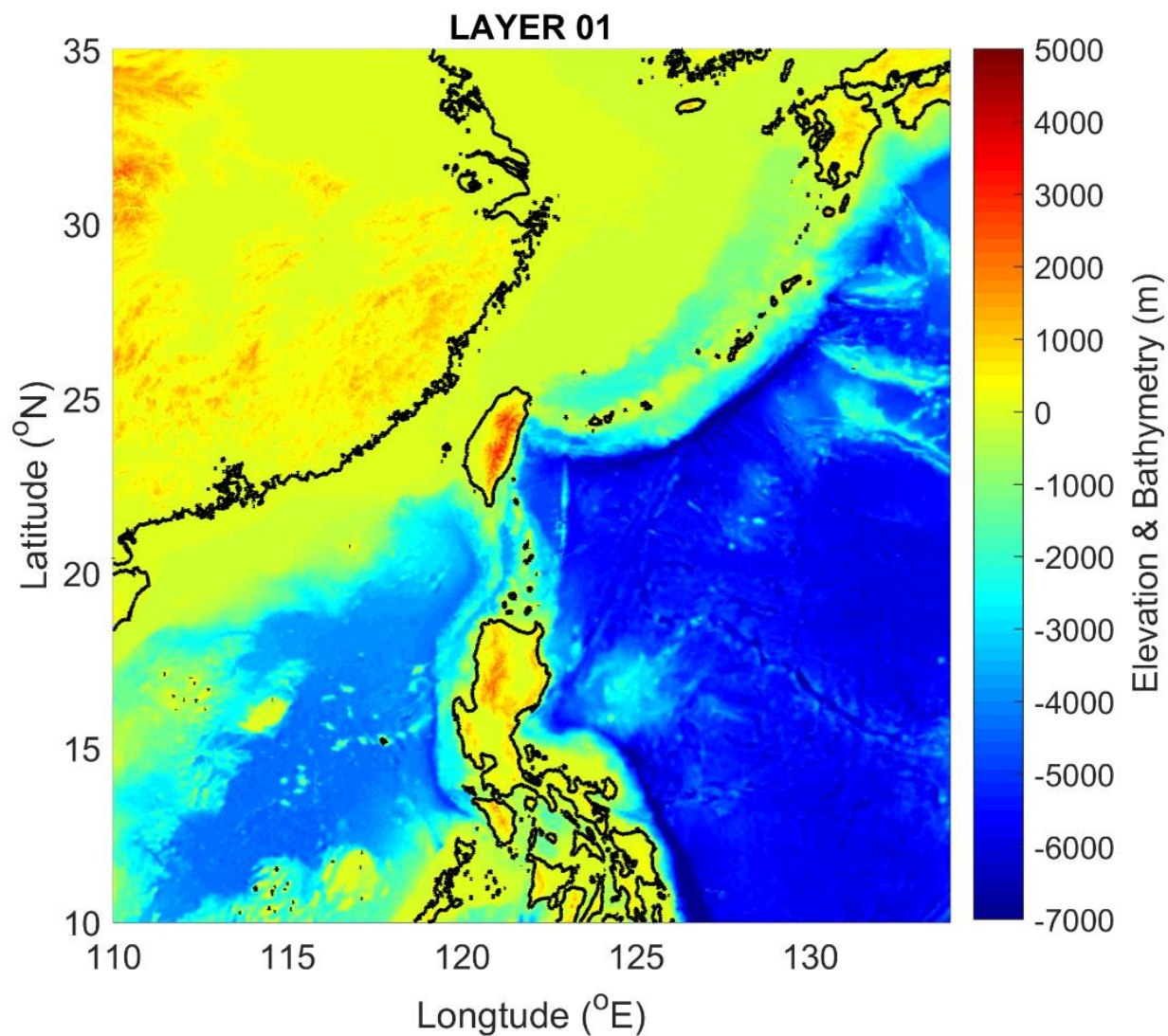
Shape Parameter

$$B = \frac{1}{P_n - P_c} \left(\frac{V_{\max}}{5.375} \right)^2$$

Radius of Maximum Wind

$$R_{\max} = \begin{cases} 42.6 - 0.86 \cdot (P_c - 990) & P_c \geq 990 \\ 51.0 - 0.84 \cdot (P_c - 980) & 980 \leq P_c < 990 \\ 58.4 - 0.74 \cdot (P_c - 970) & 970 \leq P_c < 980 \\ 63.0 - 0.46 \cdot (P_c - 960) & 960 \leq P_c < 970 \\ 70.0 - 0.234 \cdot (P_c - 930) & 930 \leq P_c < 960 \\ 80.0 - 0.167 \cdot (P_c - 870) & 870 \leq P_c < 930 \\ 80.0 & P_c < 870 \end{cases}$$

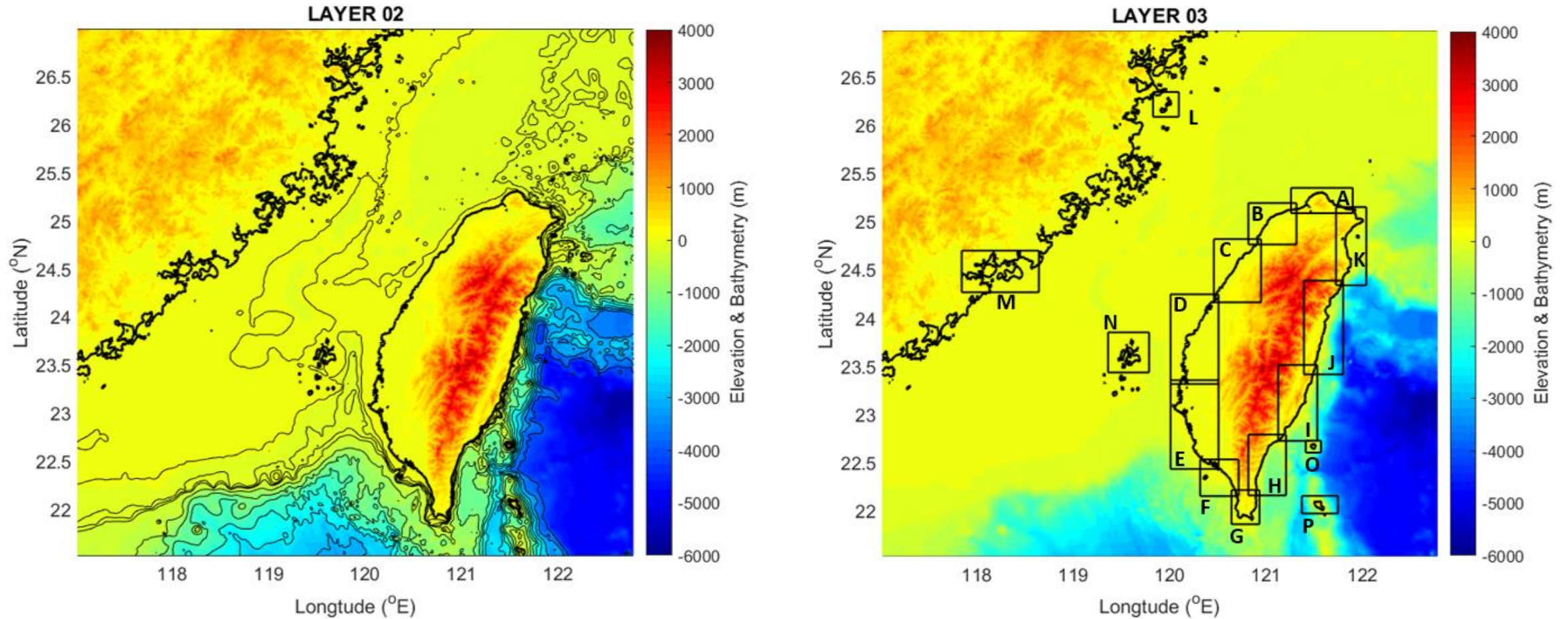
COMCOT暴潮溢淹模式之計算範圍 (1)



採用大尺度之球座標系統計算域，涵蓋颱風生命週期以及完整的風暴潮傳遞歷程。

Layer 01 is adopted to cover the complete typhoons' life cycle and full storm surge propagations.

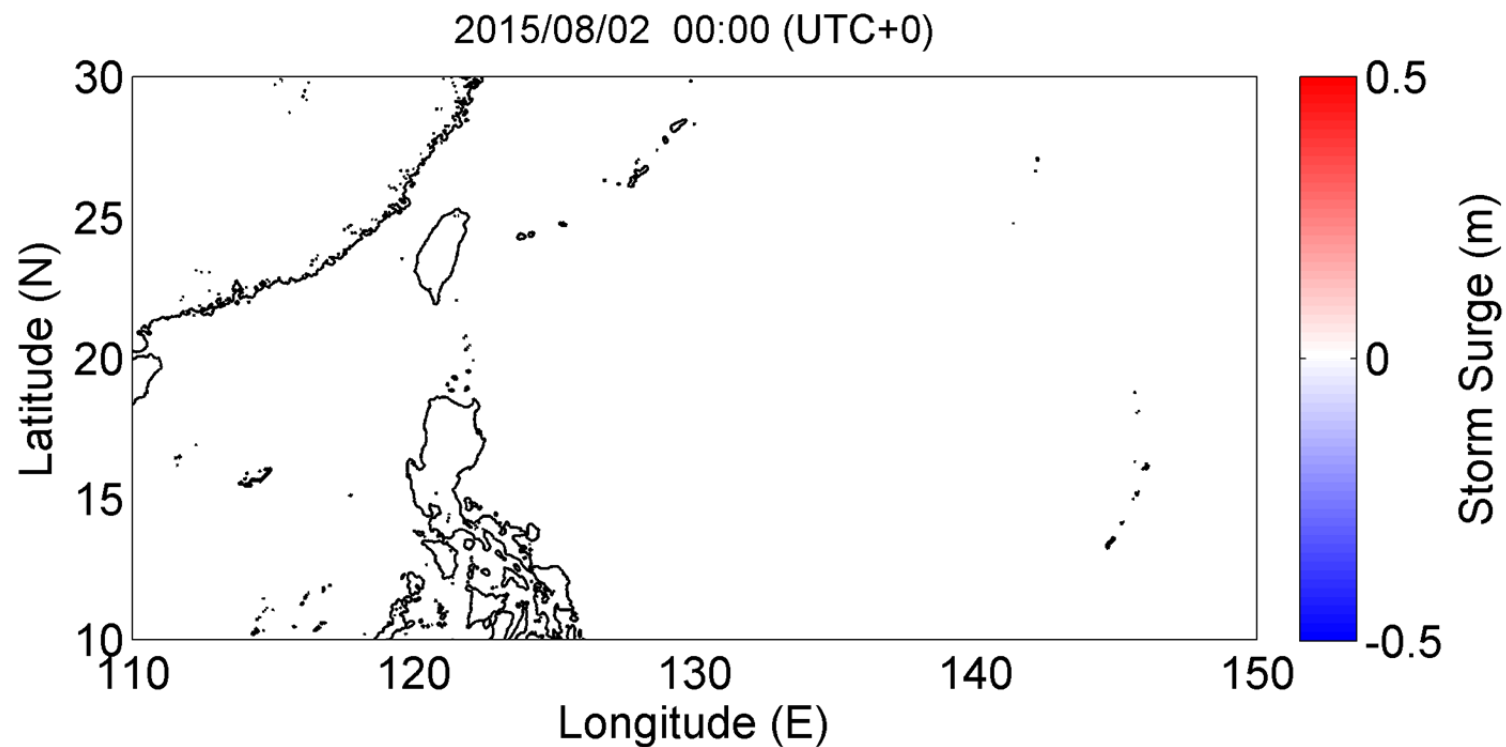
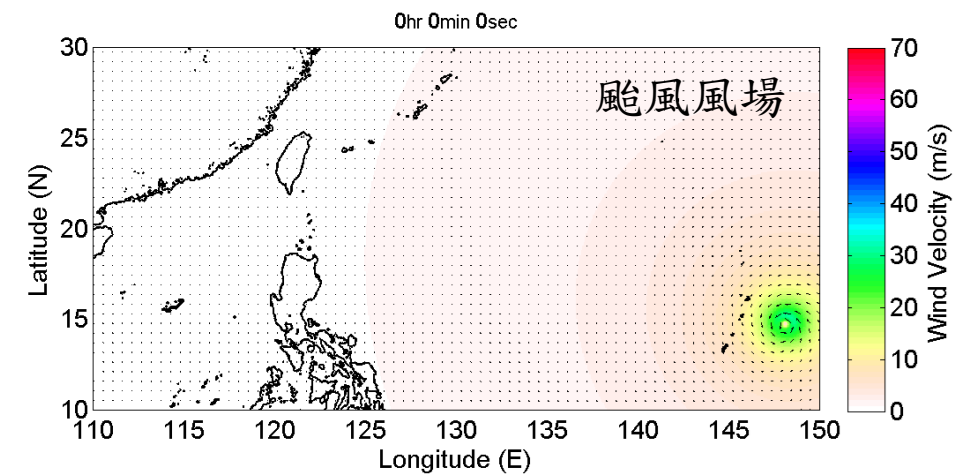
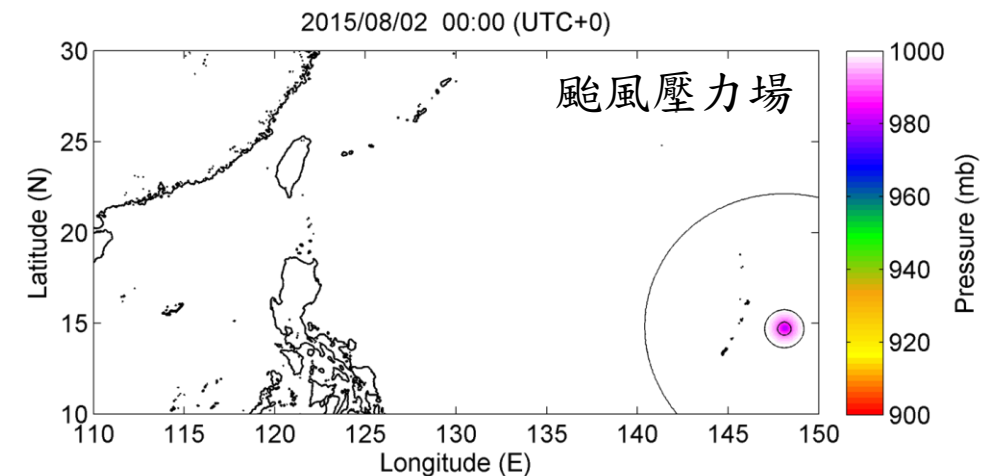
COMCOT 暴潮溢淹模式之計算範圍 (2)



Layer 02 and Layer 03 are adopted to calculate nonlinear shallow water equations with tidal effect, bottom effects, and Coriolis effect, and evaluate inundation area in the resolution of 200 meters.

球座標系統大尺度風暴潮傳遞模擬

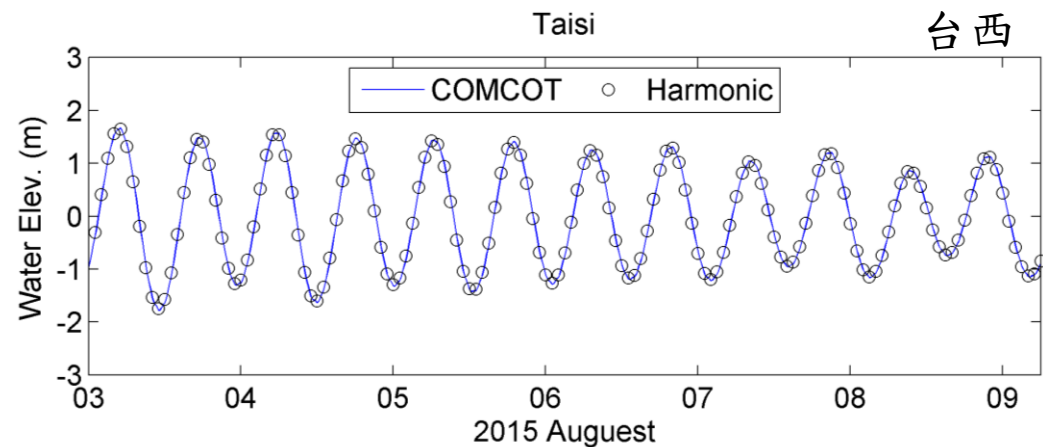
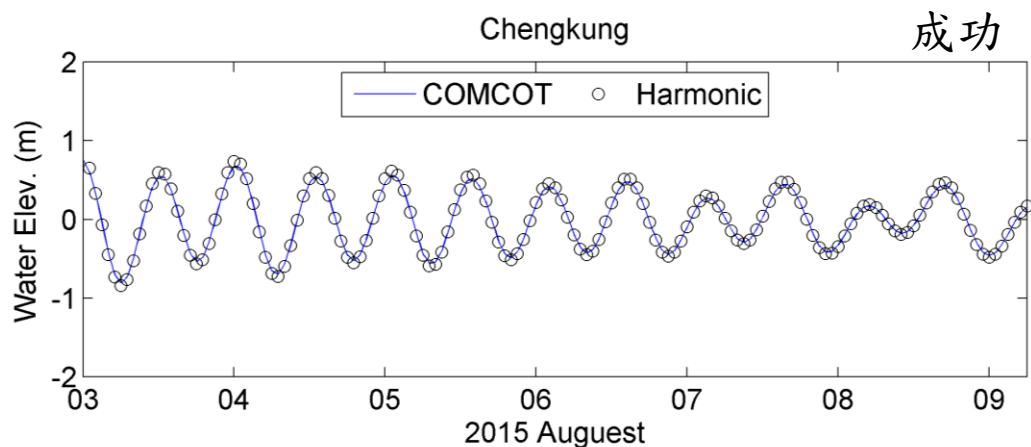
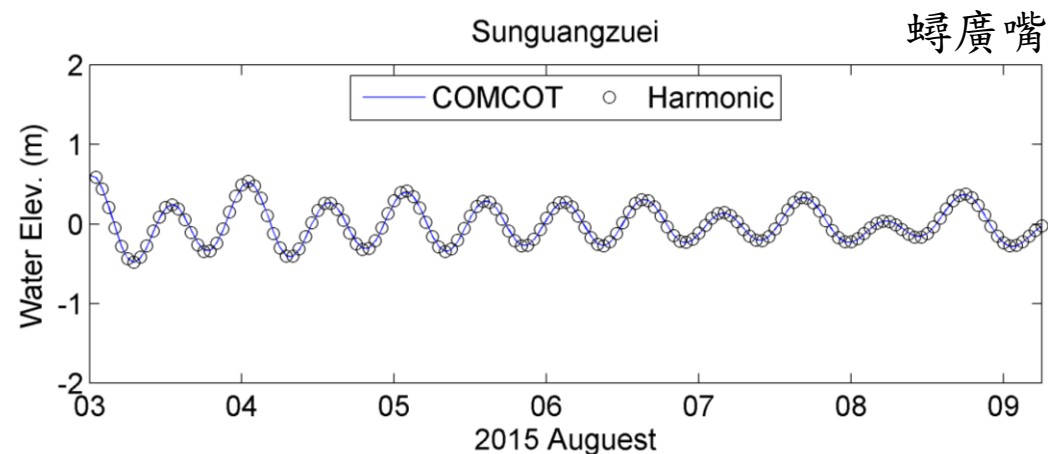
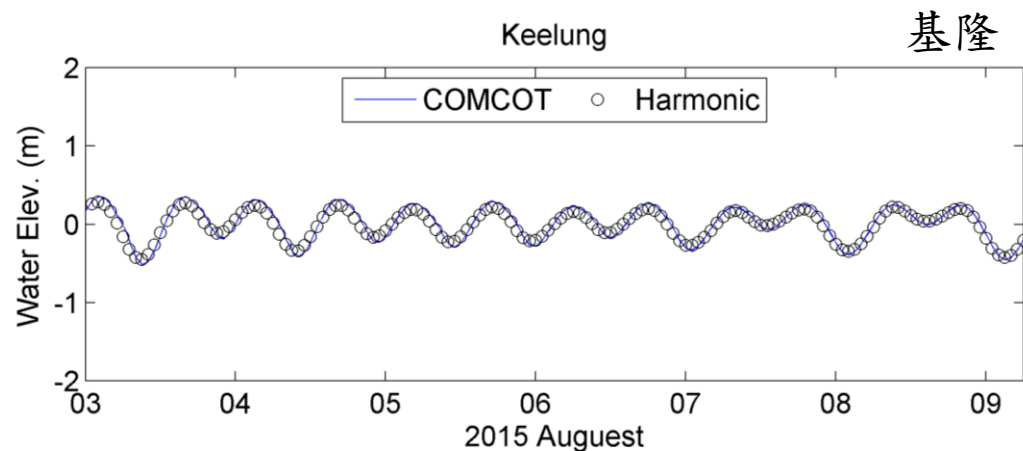
2015.08.02 00:00 – 2015.08.09 06:00 (UTC)



COMCOT暴潮溢淹模式，可自颱風甫生成時即開始模擬，至颱風生命週期結束，有效地掌握完整的風暴潮傳遞歷程。

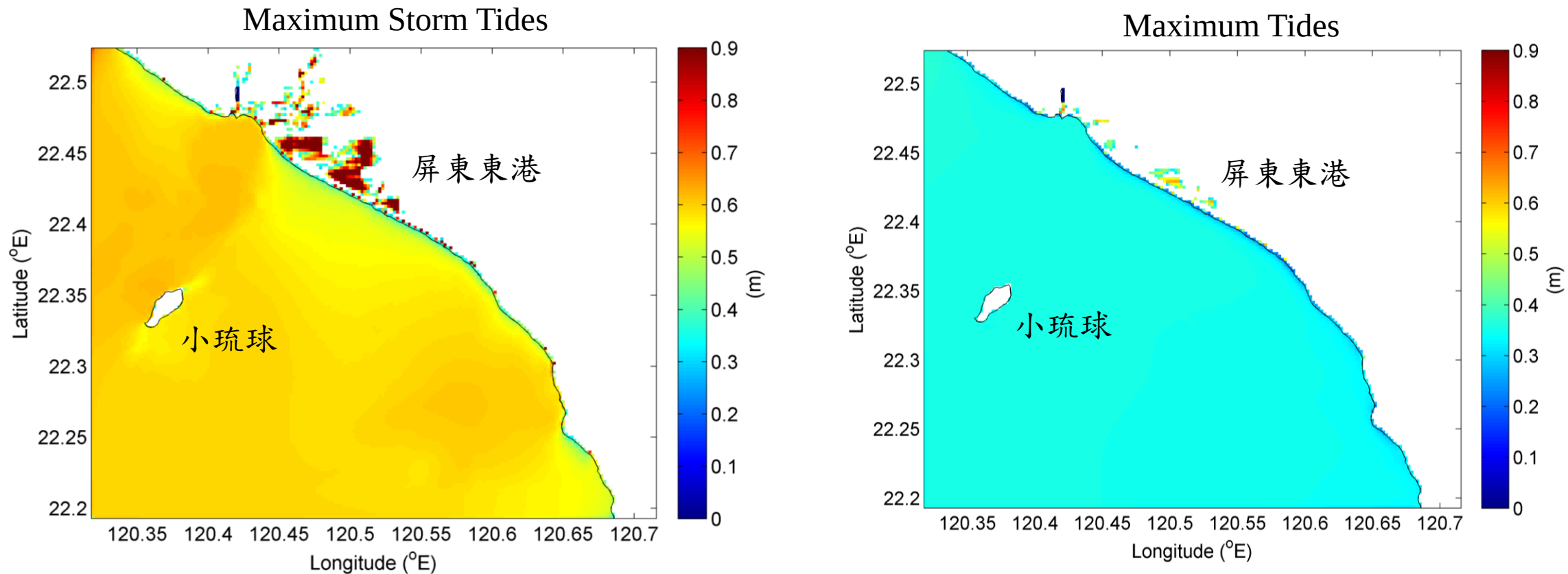
2015年蘇迪勒颱風期間潮汐校驗

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



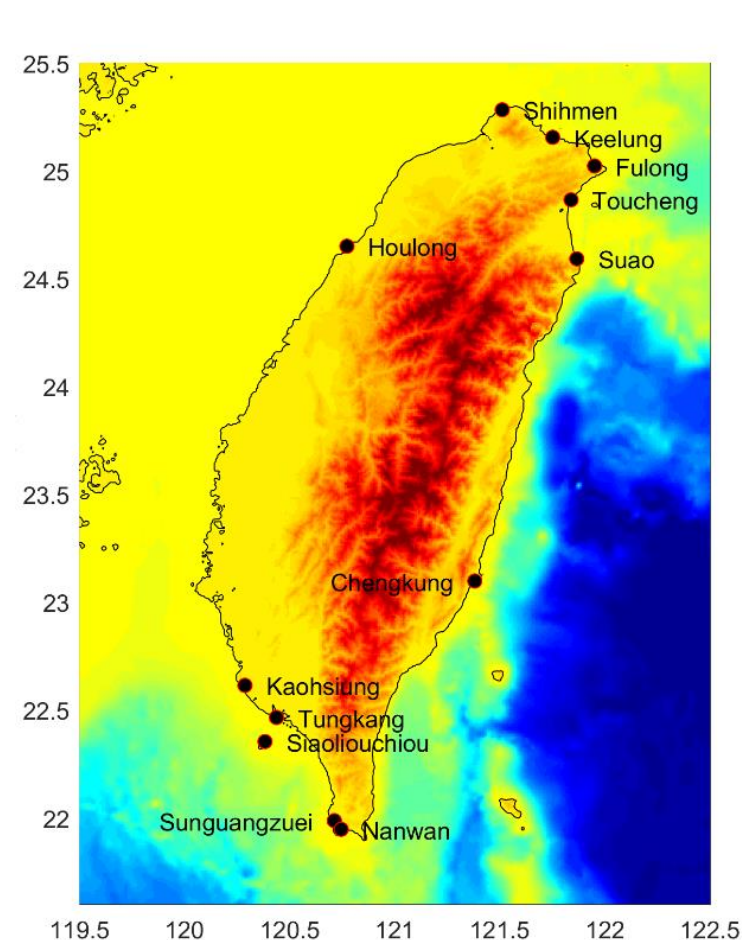
COMCOT所模擬之潮汐與調和分析結果十分吻合，突顯模式準確性，並利於後續暴潮分析。

臺灣近岸區域200公尺解析度溢淹模擬

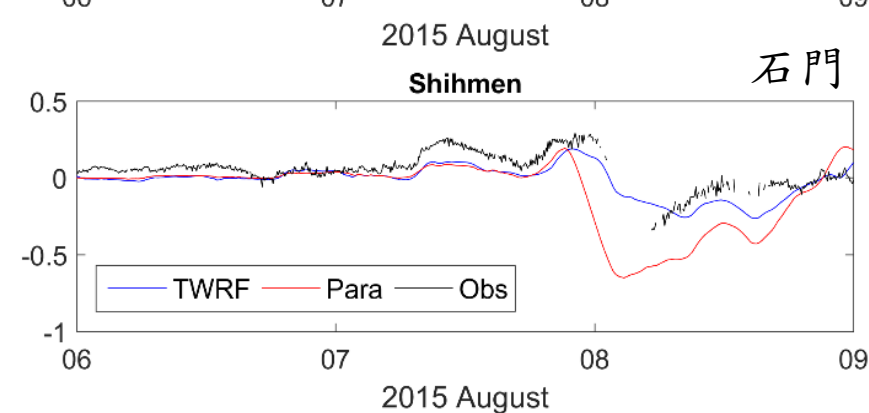
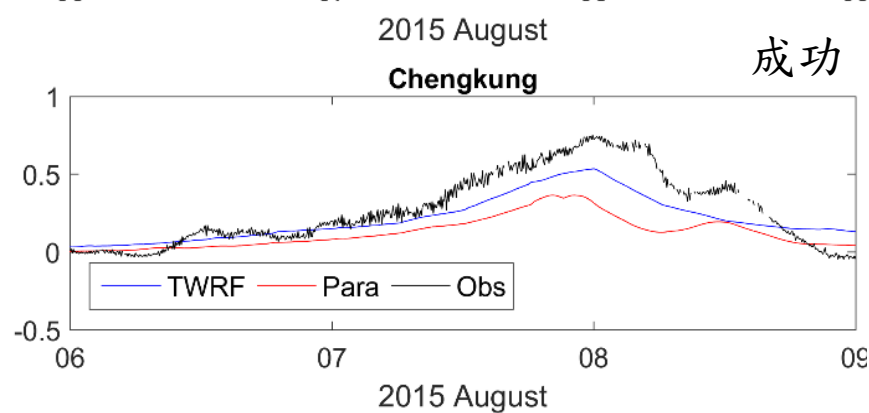
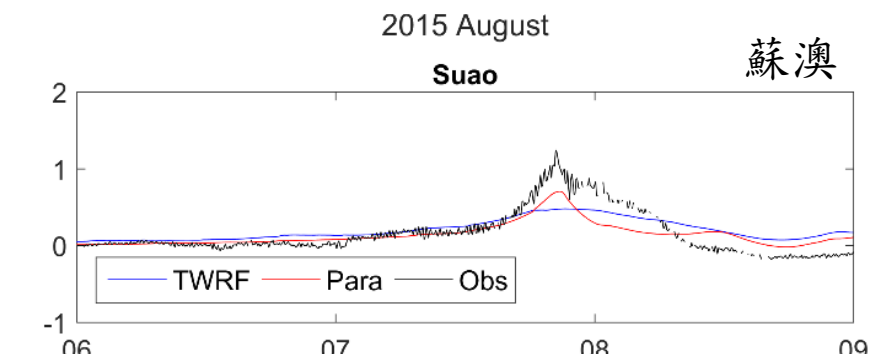
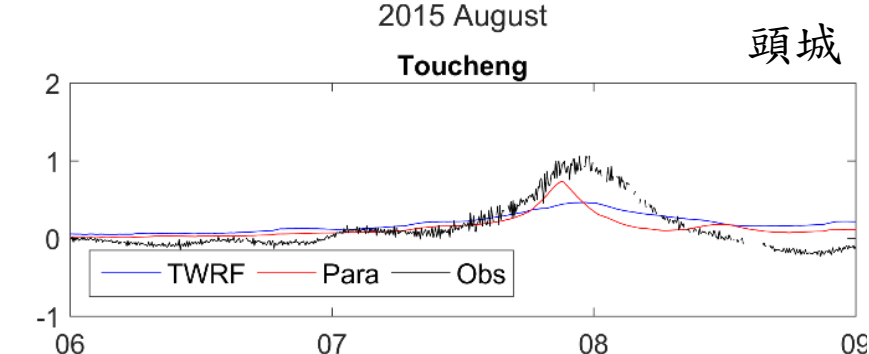
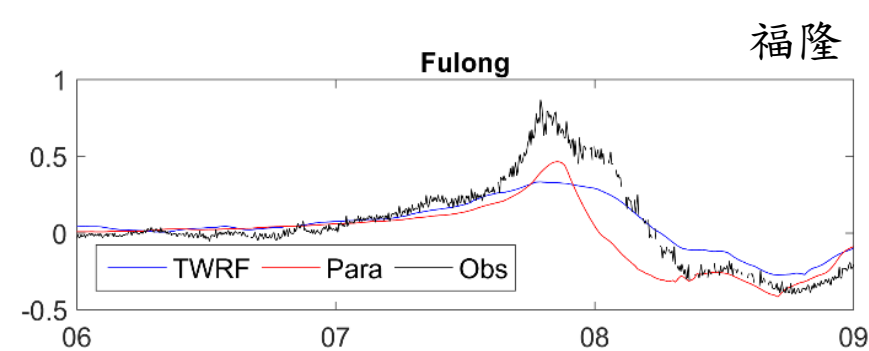
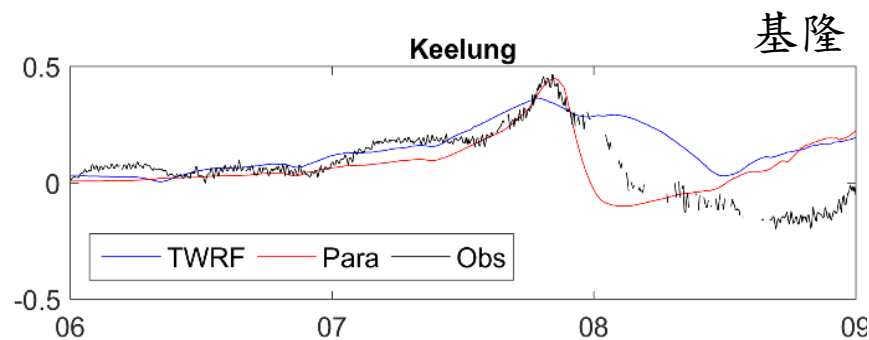


2015年蘇迪勒颱風期間，屏東東港沿海區域之模擬結果；左圖為最大暴潮總水位（Maximum Storm Tides），右圖為最大潮汐高（Maximum Tide），顏色代表潮高，單位為公尺，黑色實線表示數值海岸線。

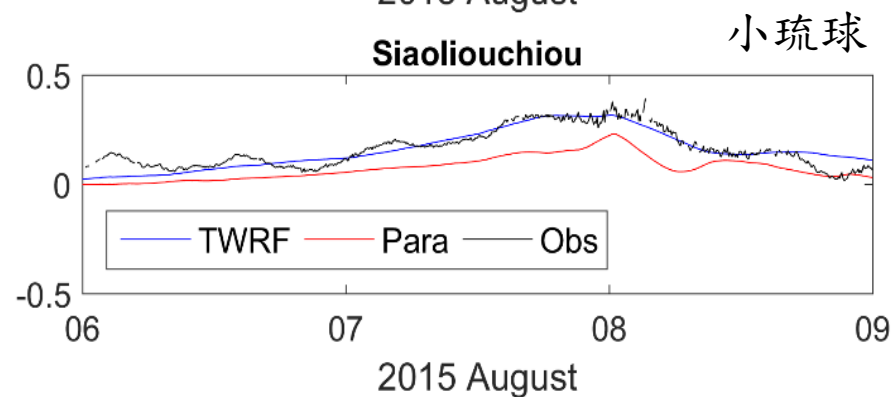
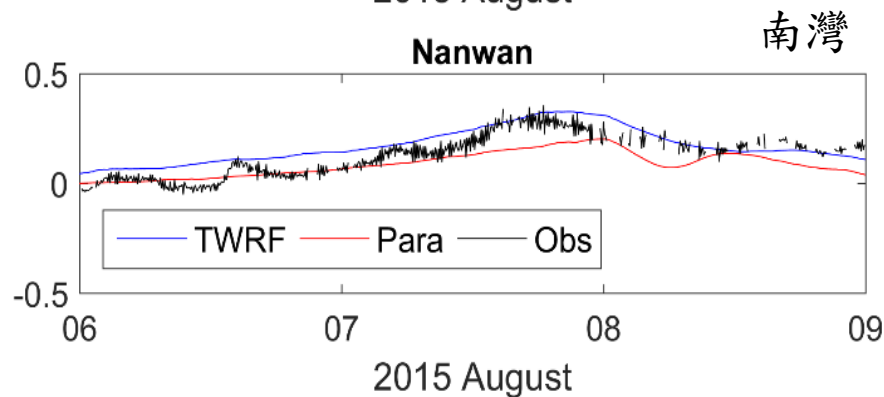
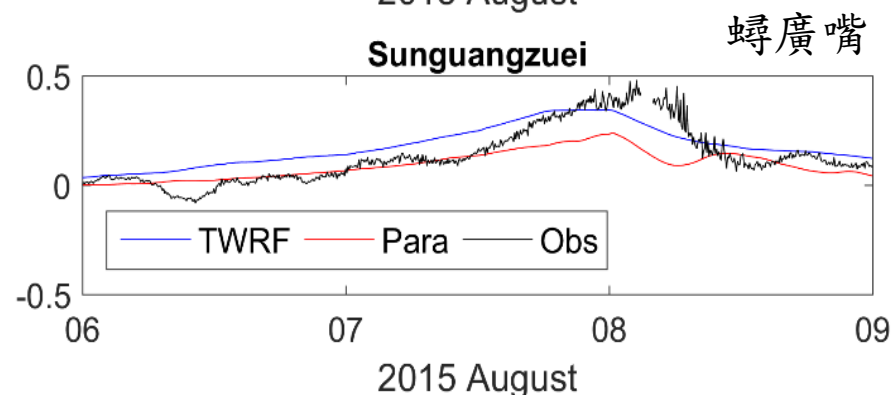
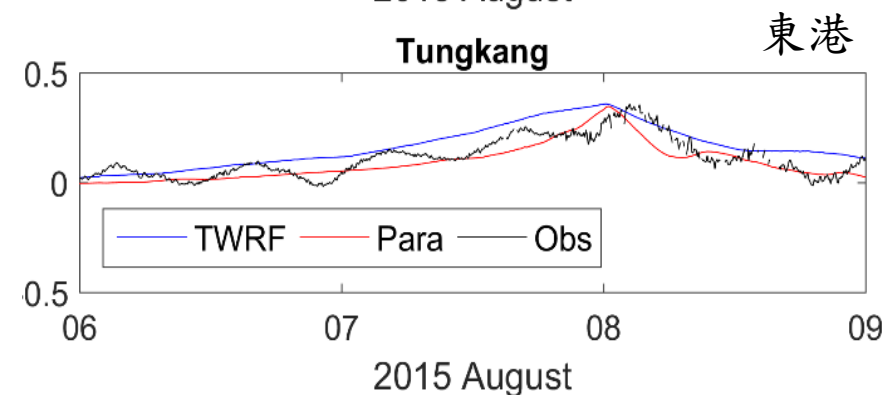
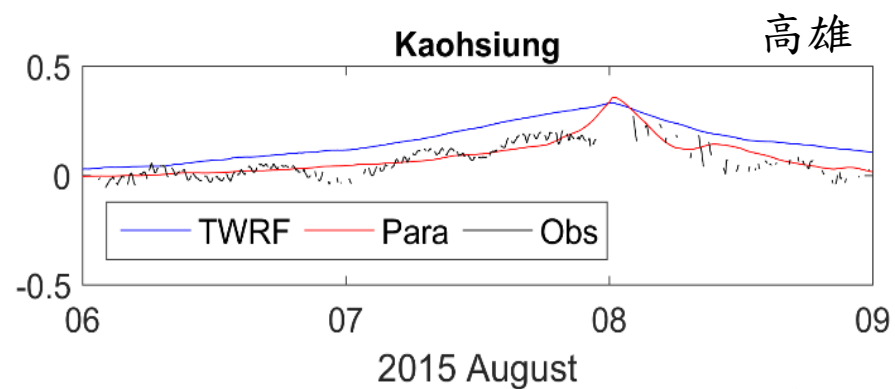
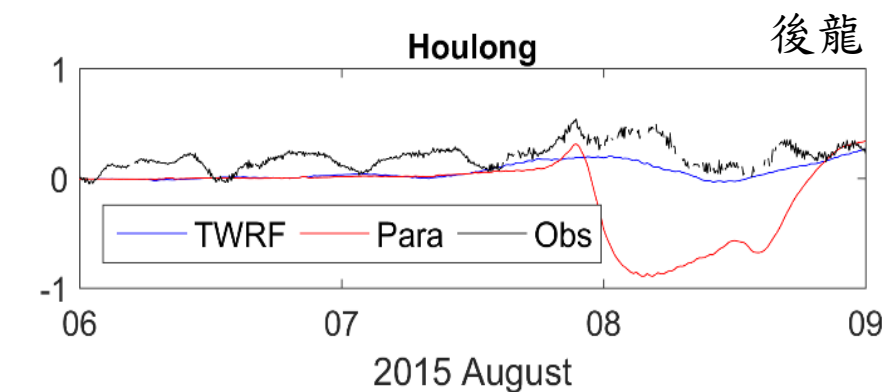
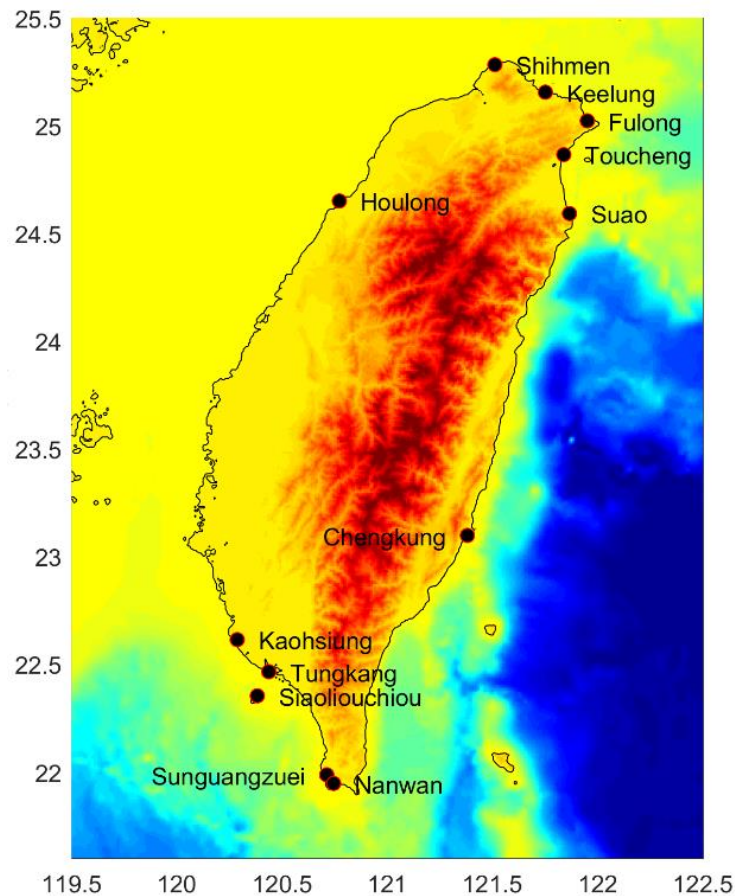
模擬結果與觀測資料之比較(東部與北部)



颱風期間之觀測資料，由中央氣象局海象測報中心所提供。

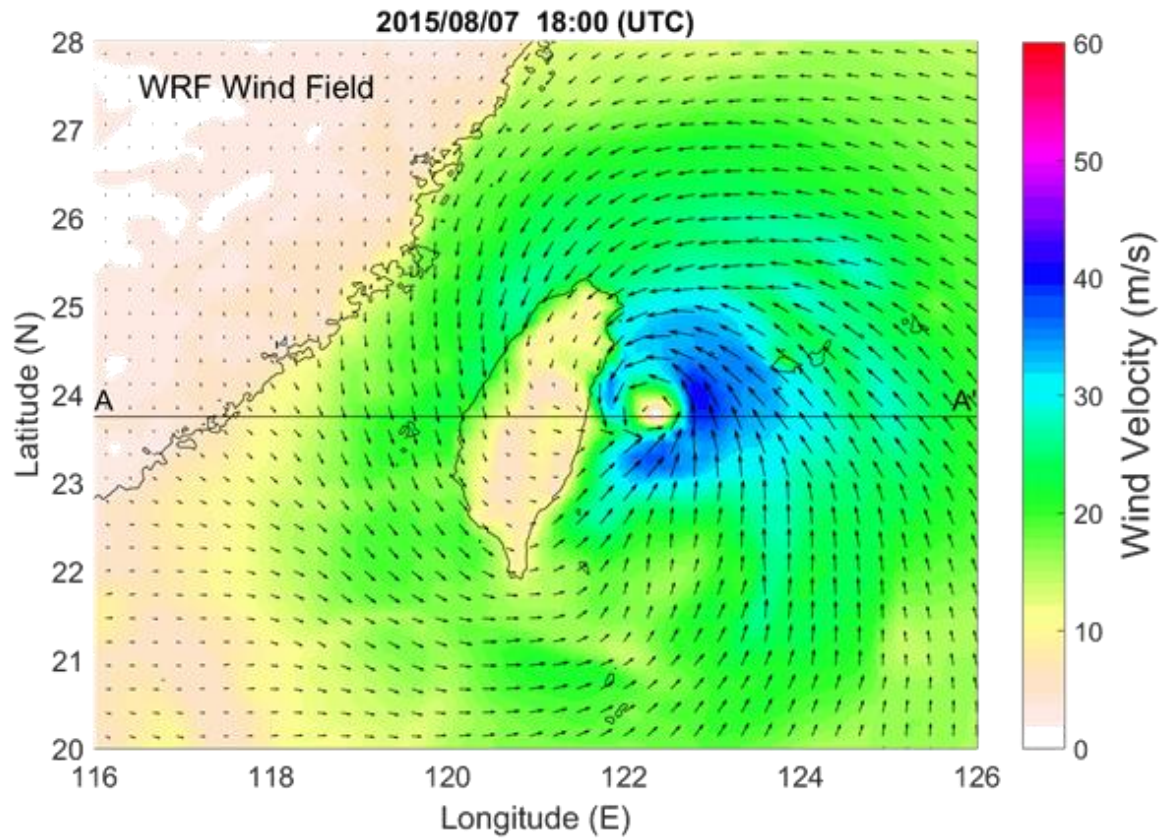


模擬結果與觀測資料之比較(西部與西南部)

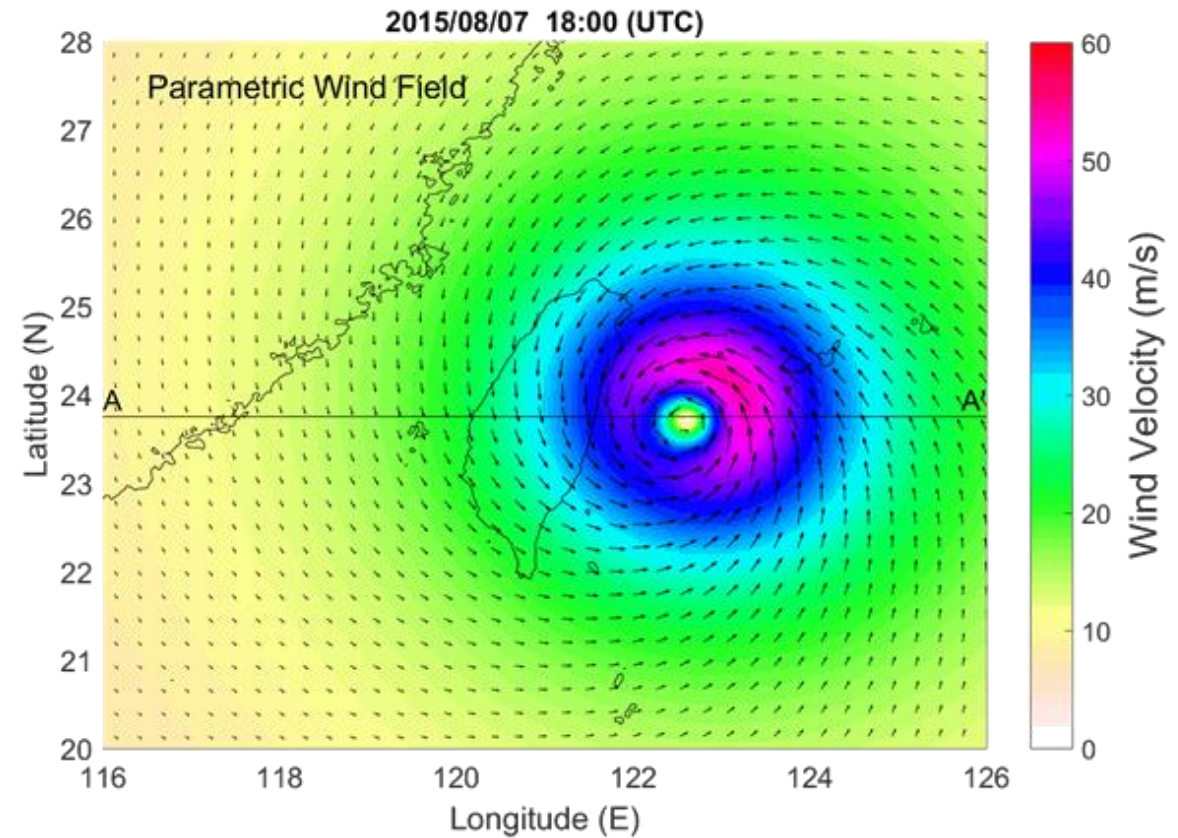


蘇迪勒登陸前後於不同颱風模式之差異

WRF Wind Field

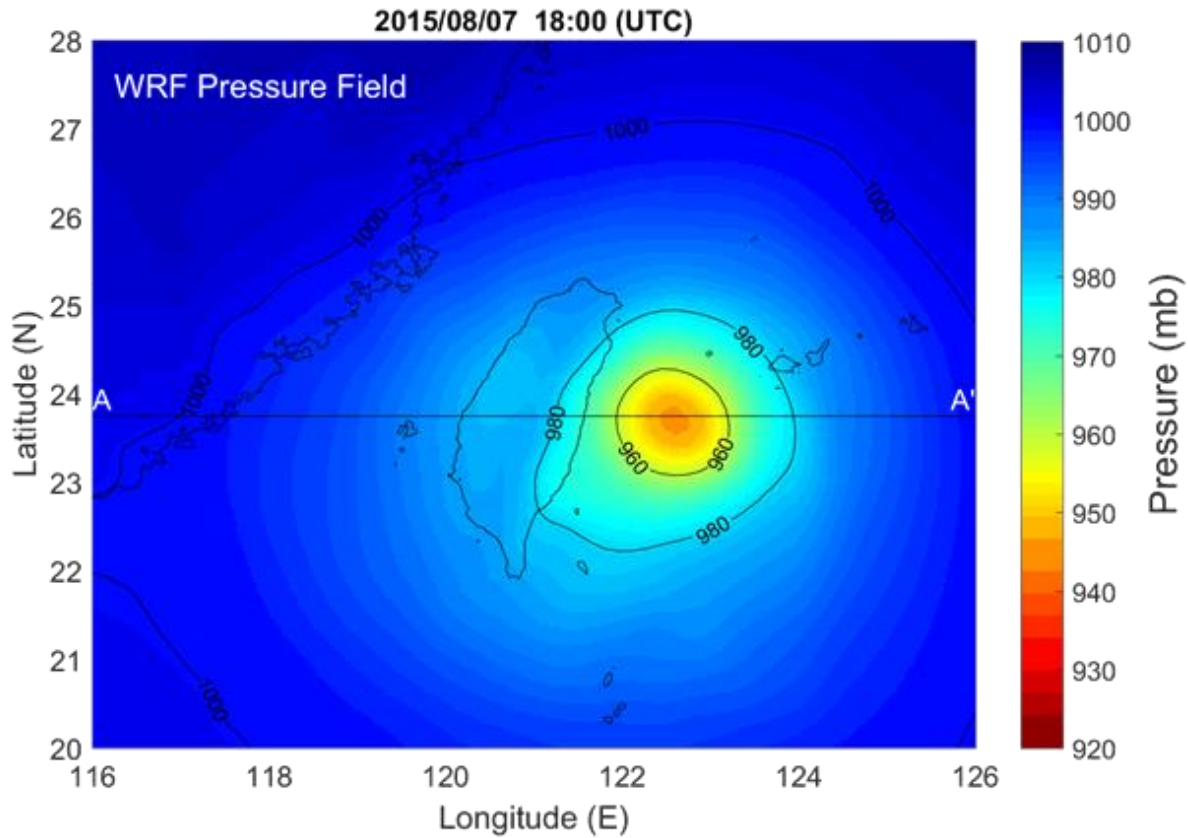


Parametric Wind Field

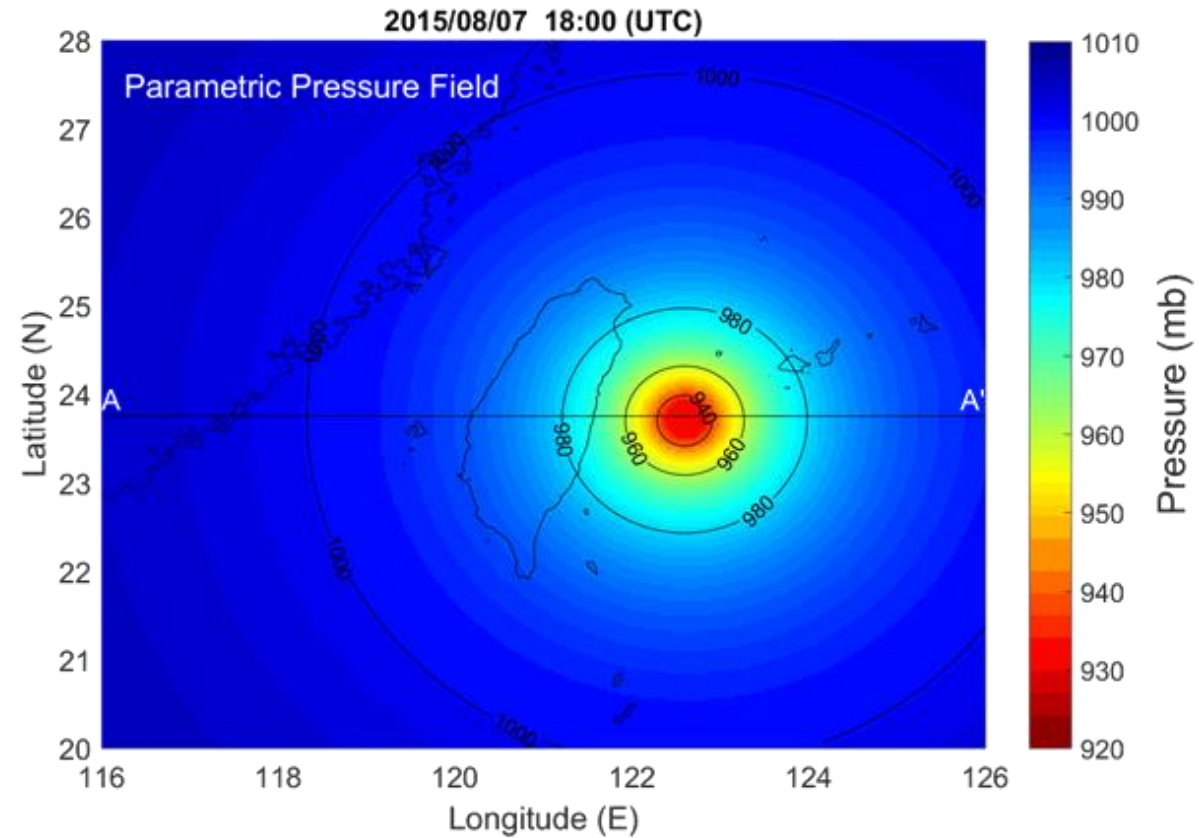


蘇迪勒登陸前後於不同颱風模式之差異

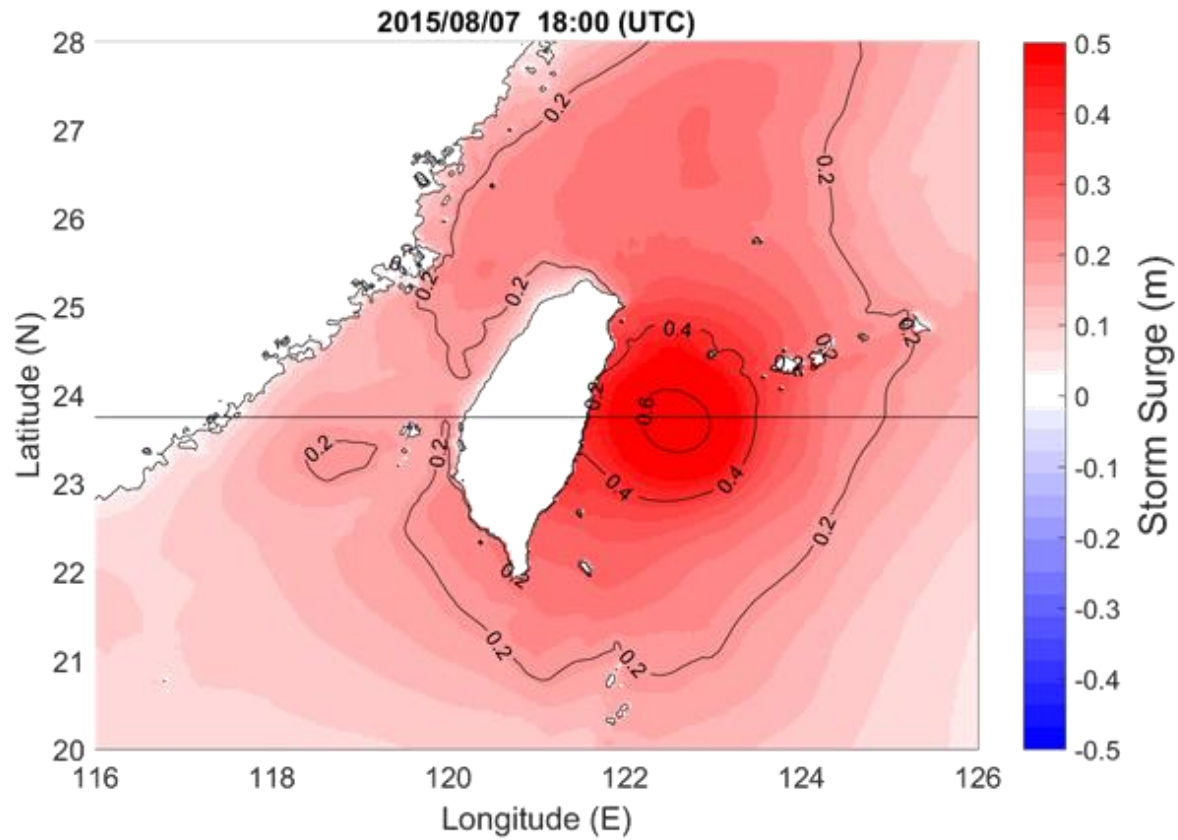
WRF Pressure Field



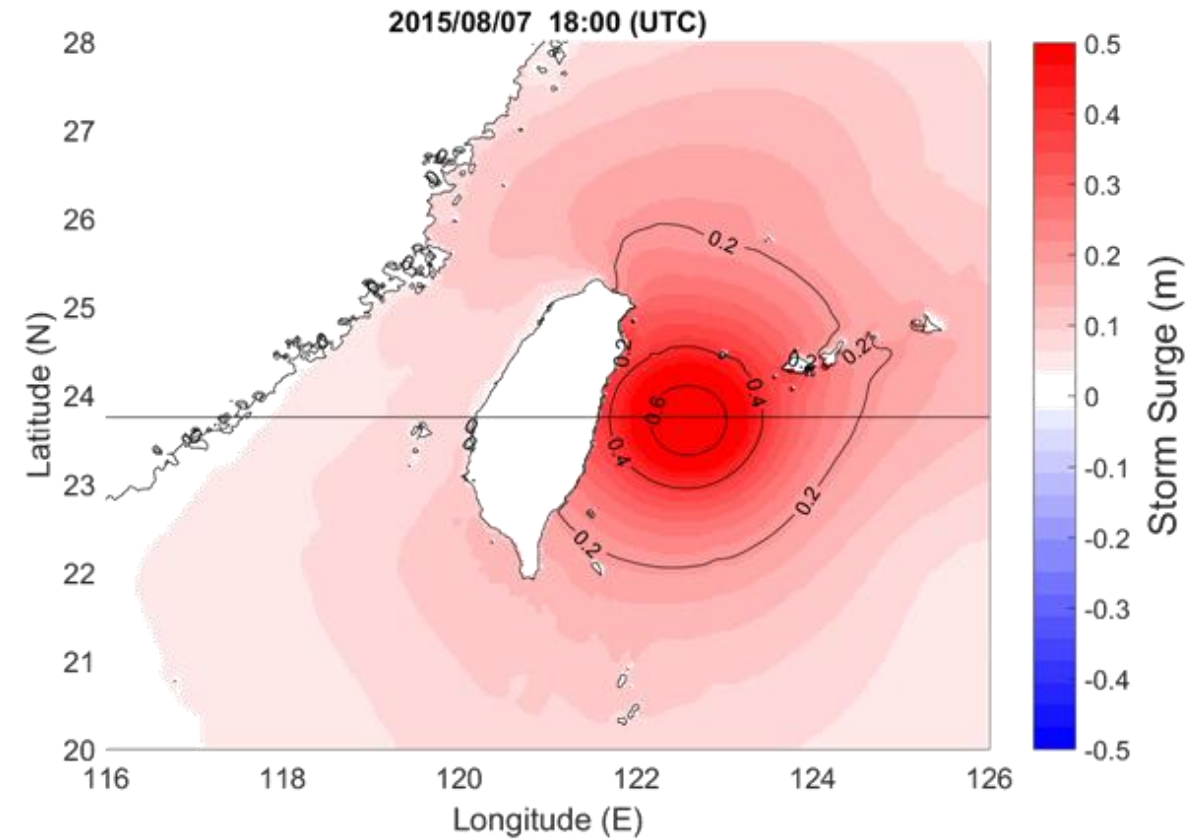
Parametric Pressure Field



Storm Surge Triggered by WRF Field

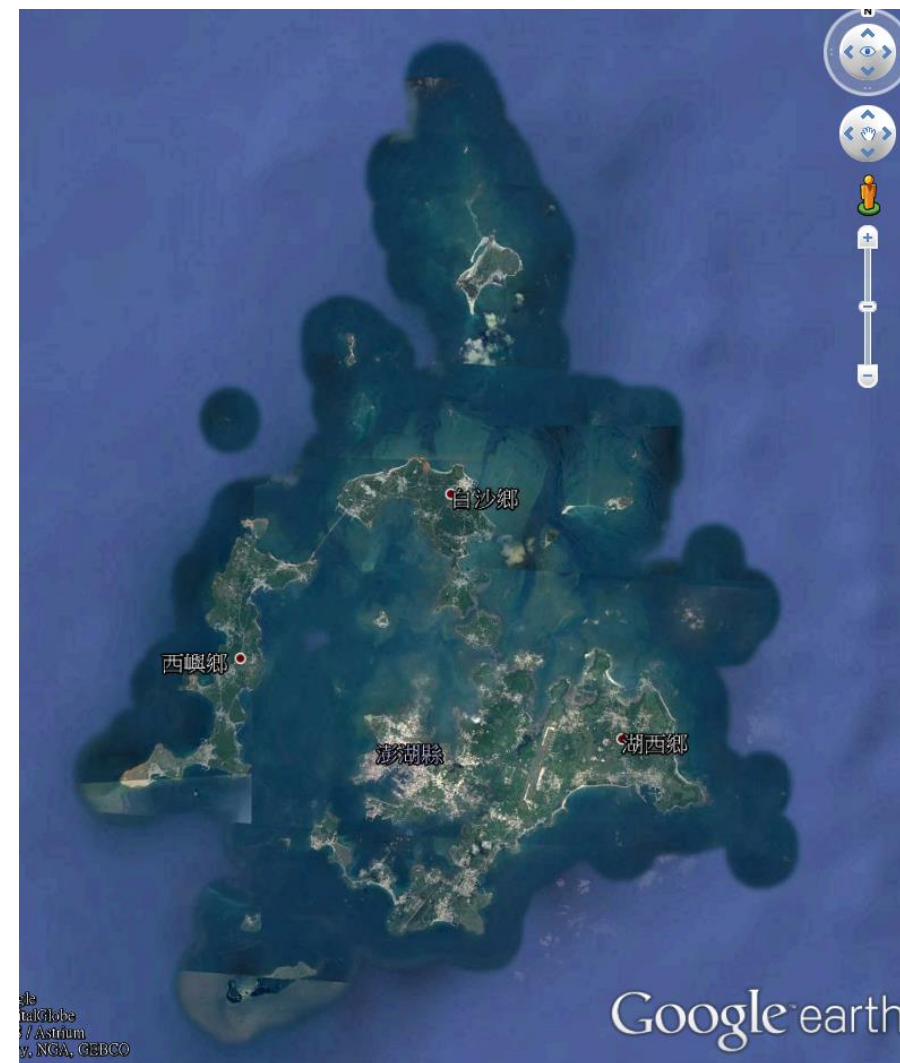
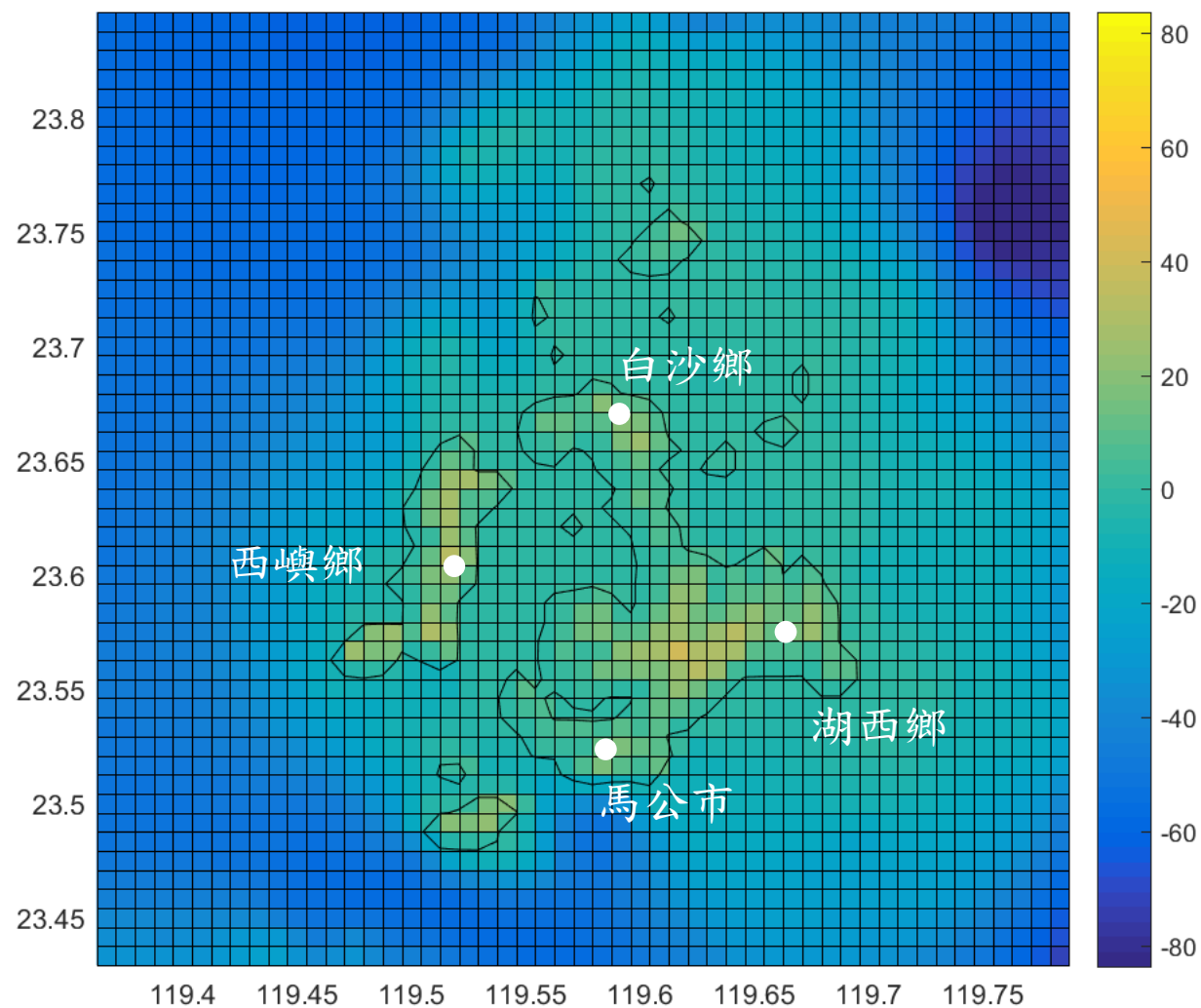


Storm Surge Triggered by Parametric Field

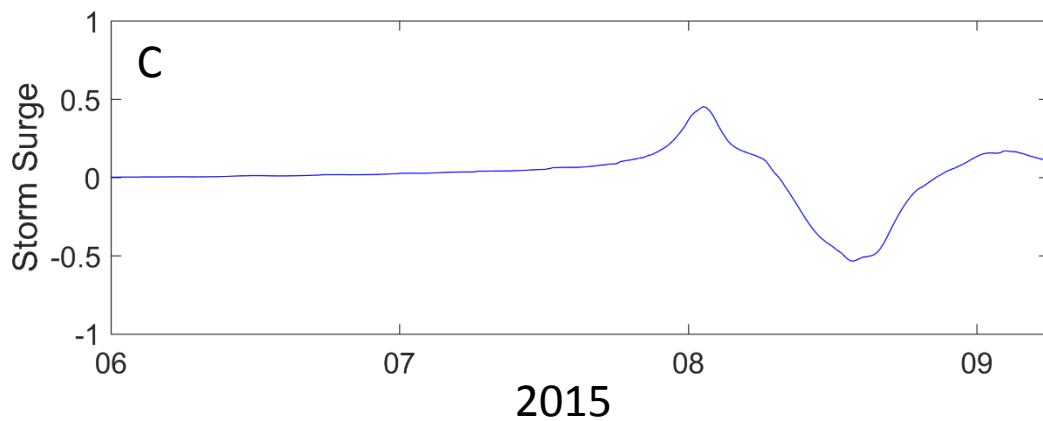
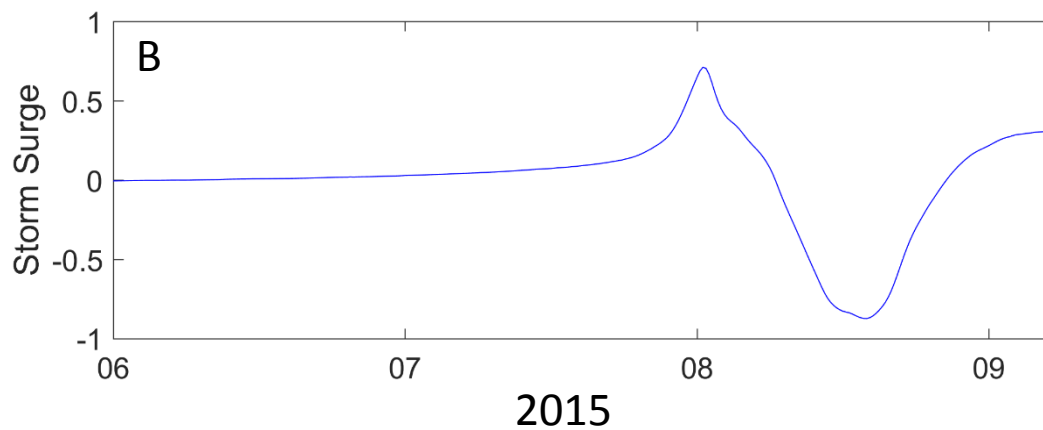
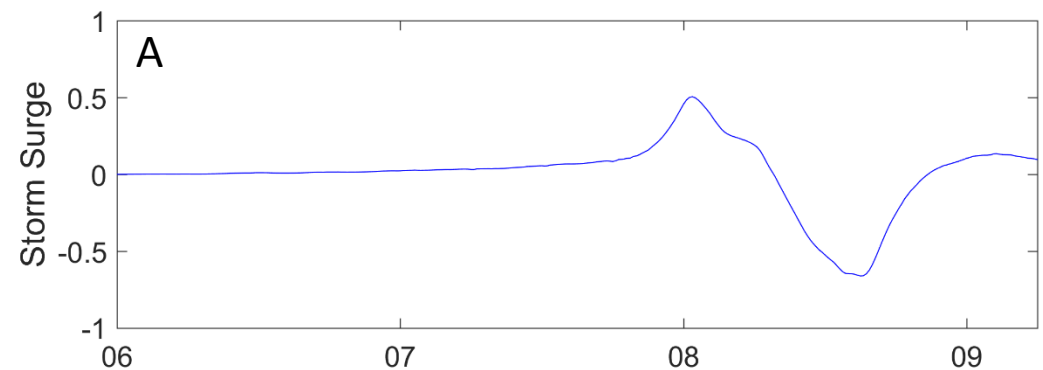
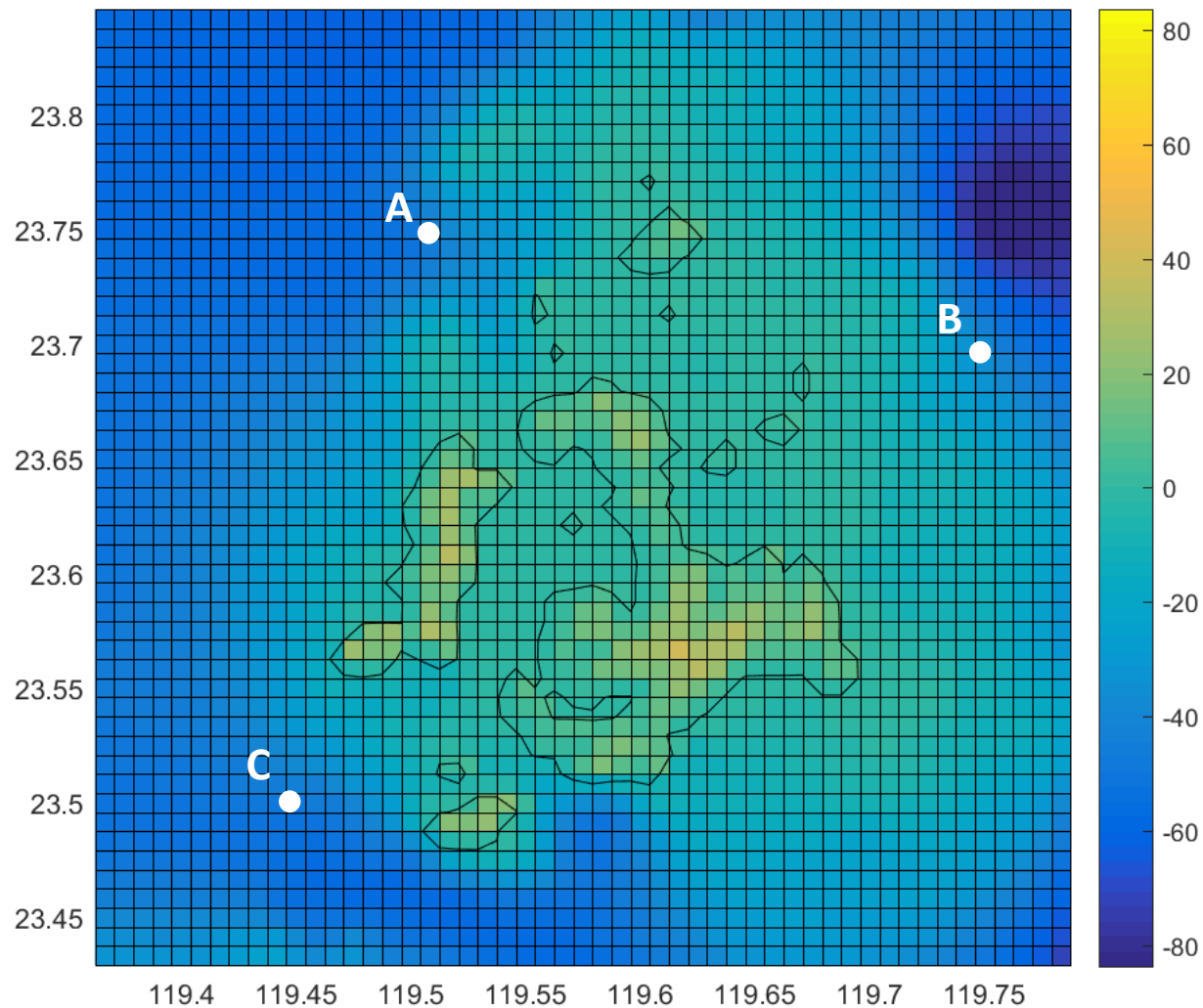


澎湖區域之計算網格配置

總網格數：2652 / 解析度：1公里



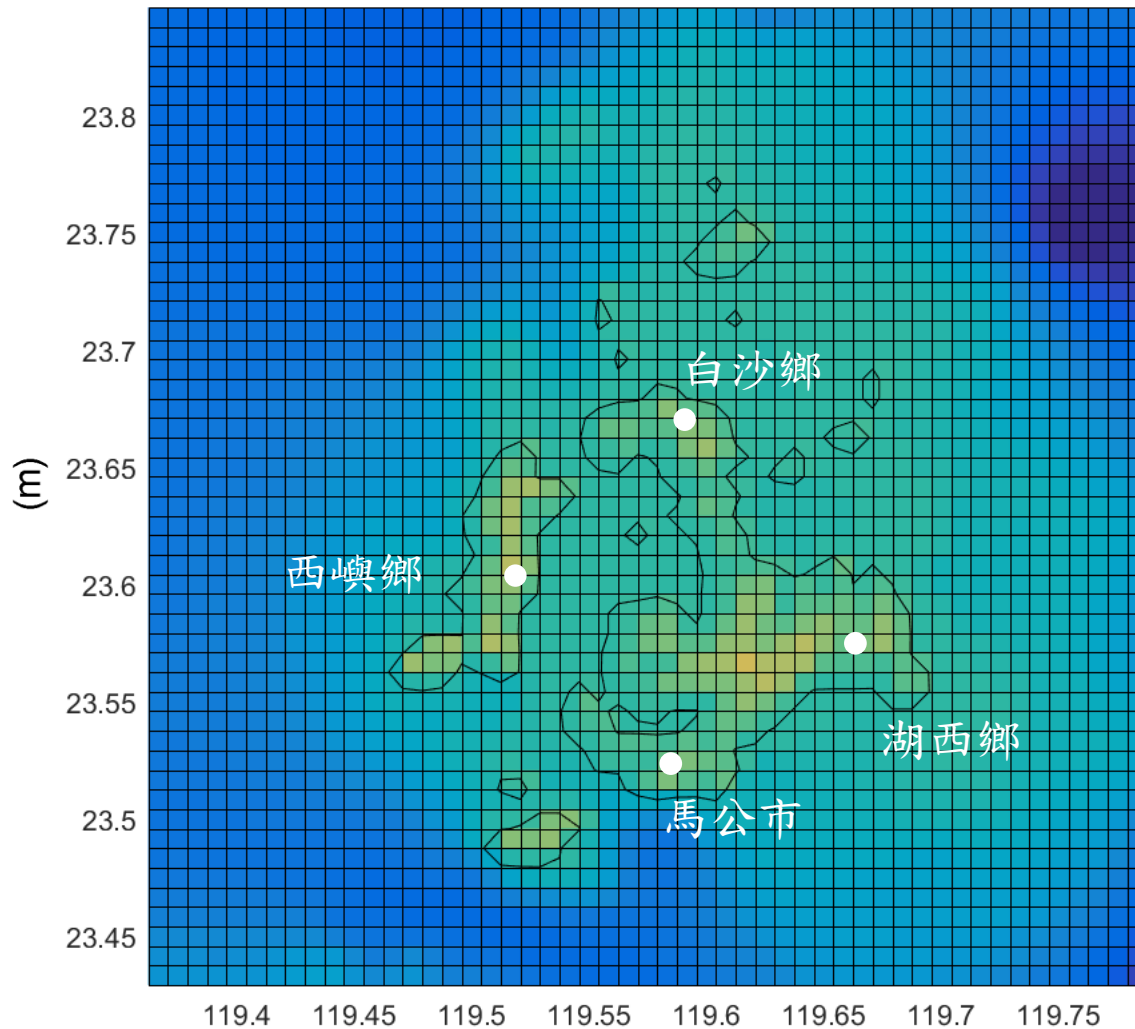
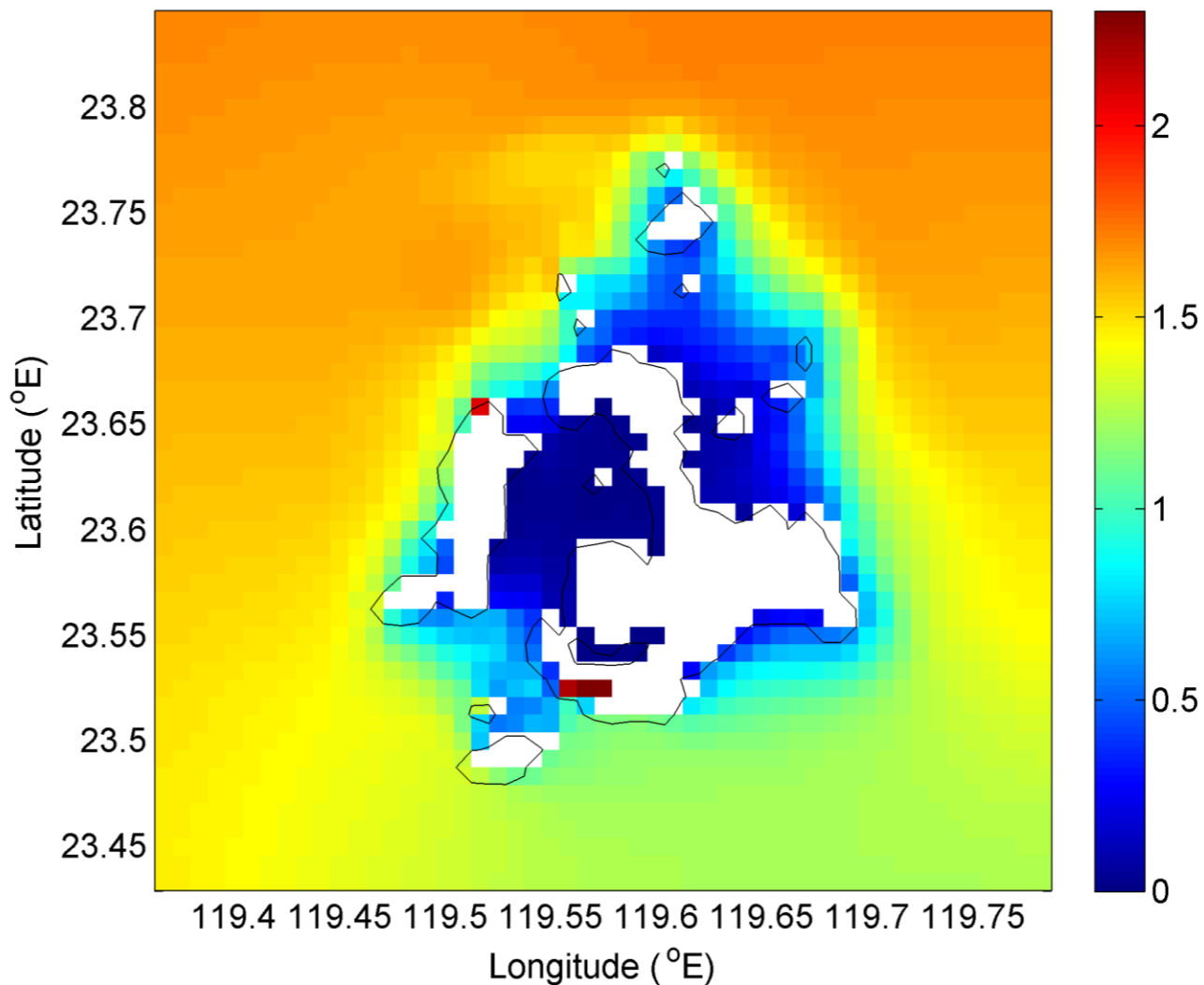
風暴潮於澎湖區域時序分析



初步分析，2015年蘇迪勒颱風所造成之風暴潮，於外海有30公分至70公分不等。

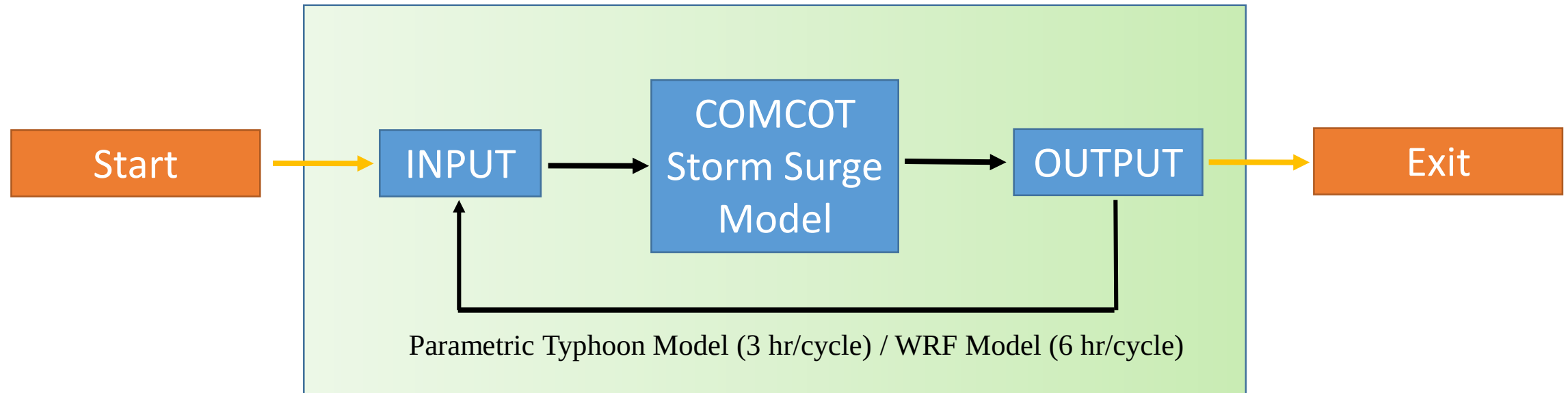
澎湖區域風暴潮模擬結果

Maximum Storm Tides



風暴潮作業化系統之流程

COMCOT風暴潮溢淹預報模式目前自2016年起，為中央氣象局所採用暴潮預報模式之一。



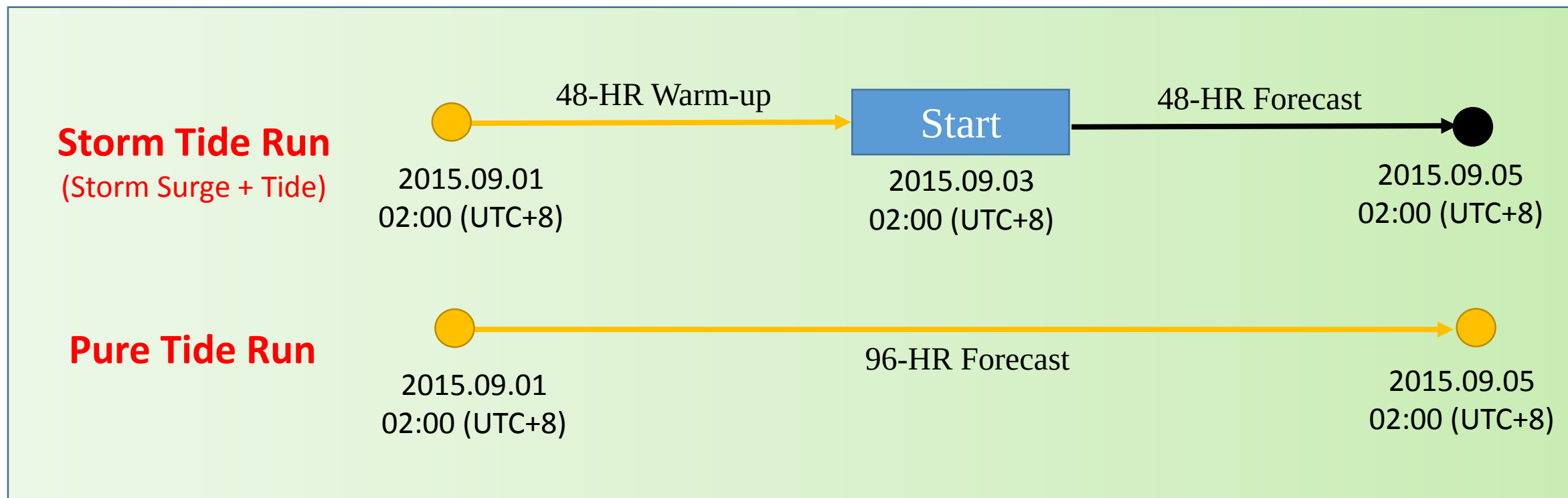
INPUT

- 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.

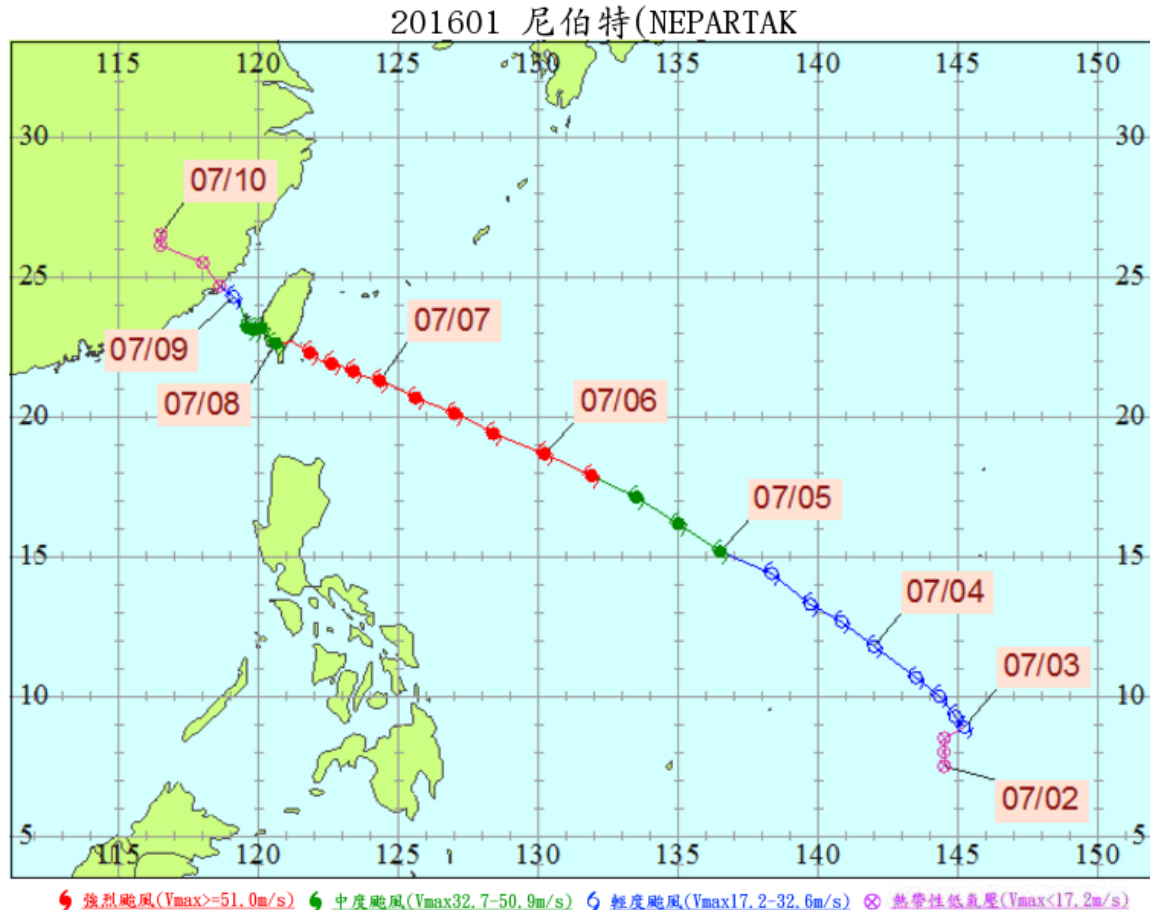
風暴潮預報作業之示意圖



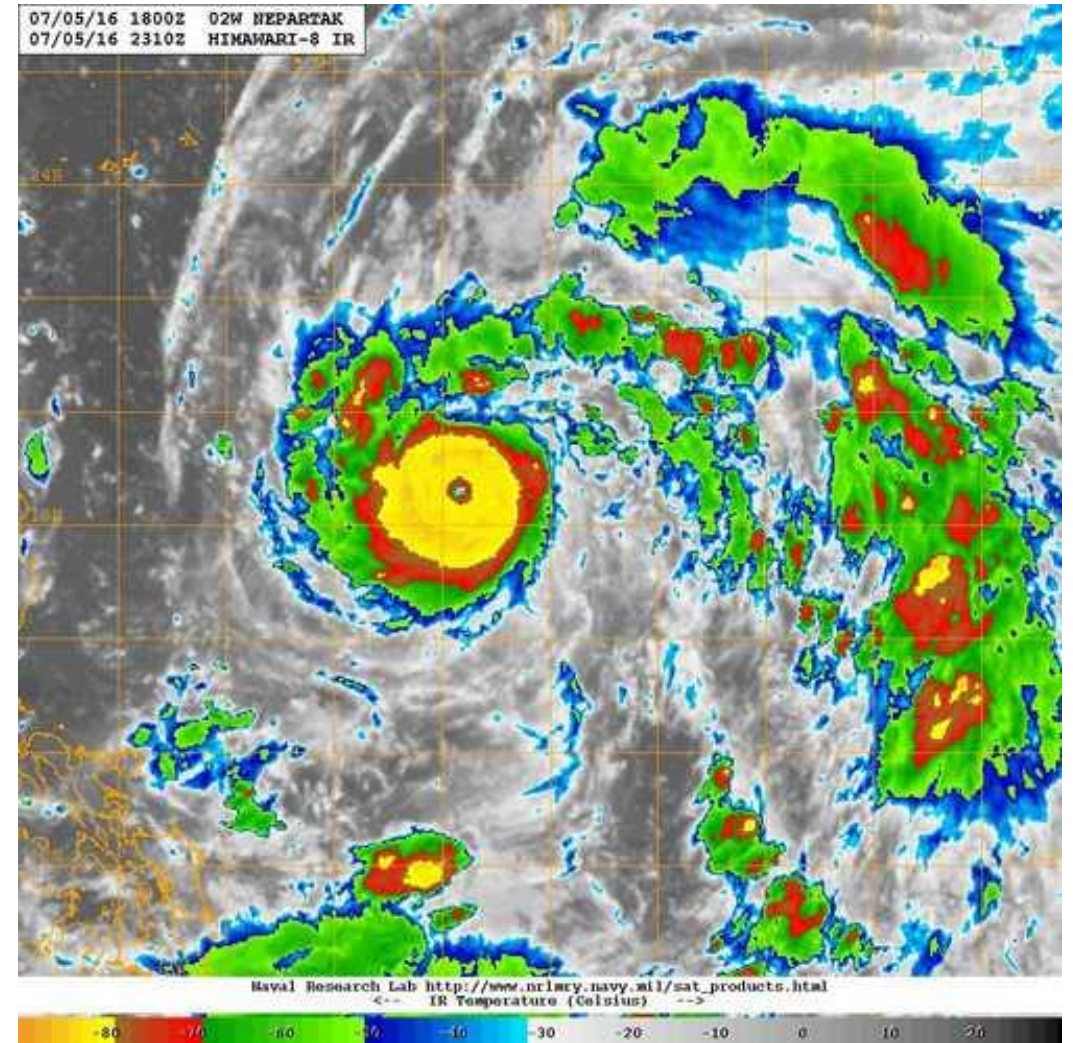
1. Every forecasting includes two 96-HR computations, and one for storm tide (storm surge + tide) run and another for pure tide run.
2. There are 48-HR warm-up and 48-HR forecast at each storm tide run.

2016年強烈颱風尼伯特之預報案例

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

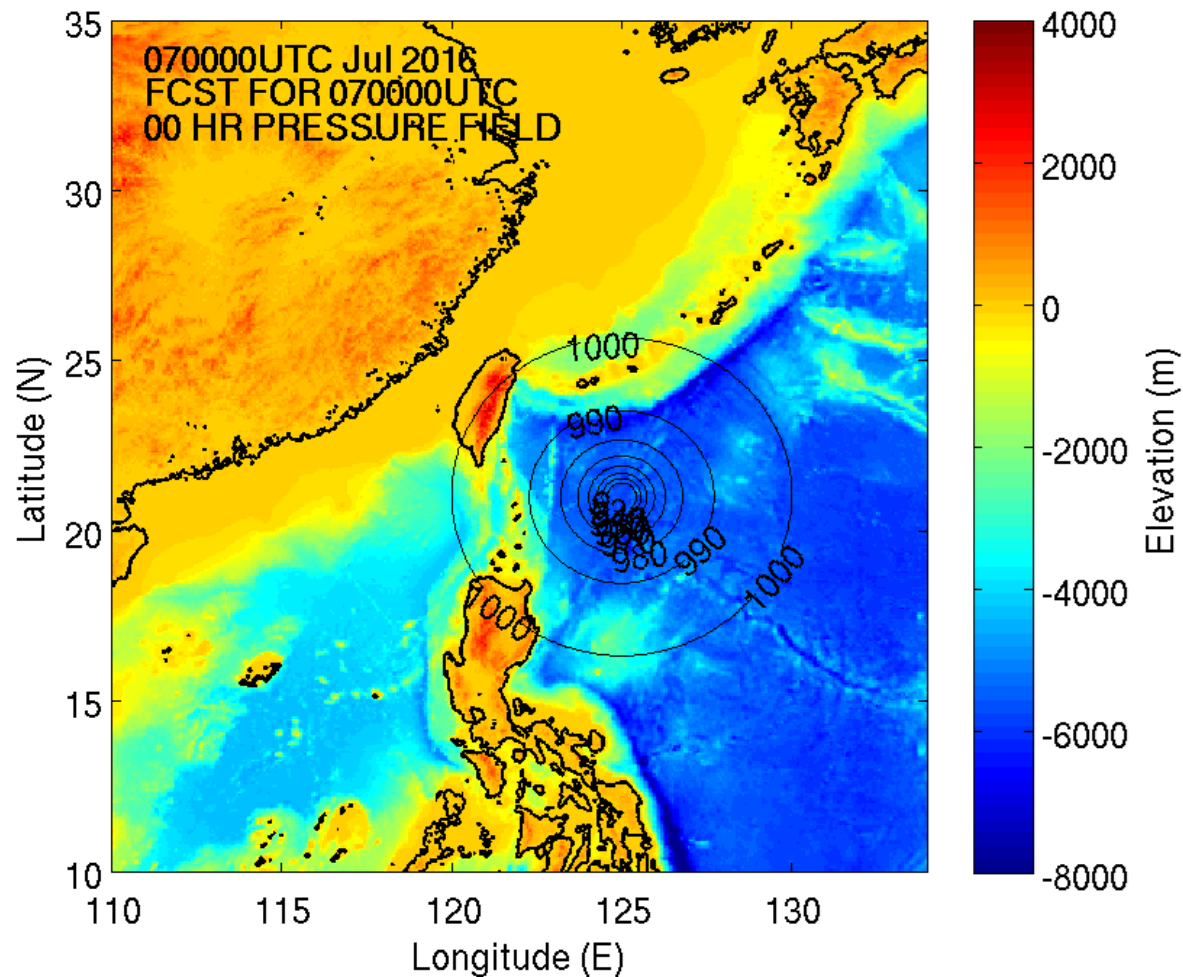


The track of Typhoon Nepartak (CWB, Taiwan)

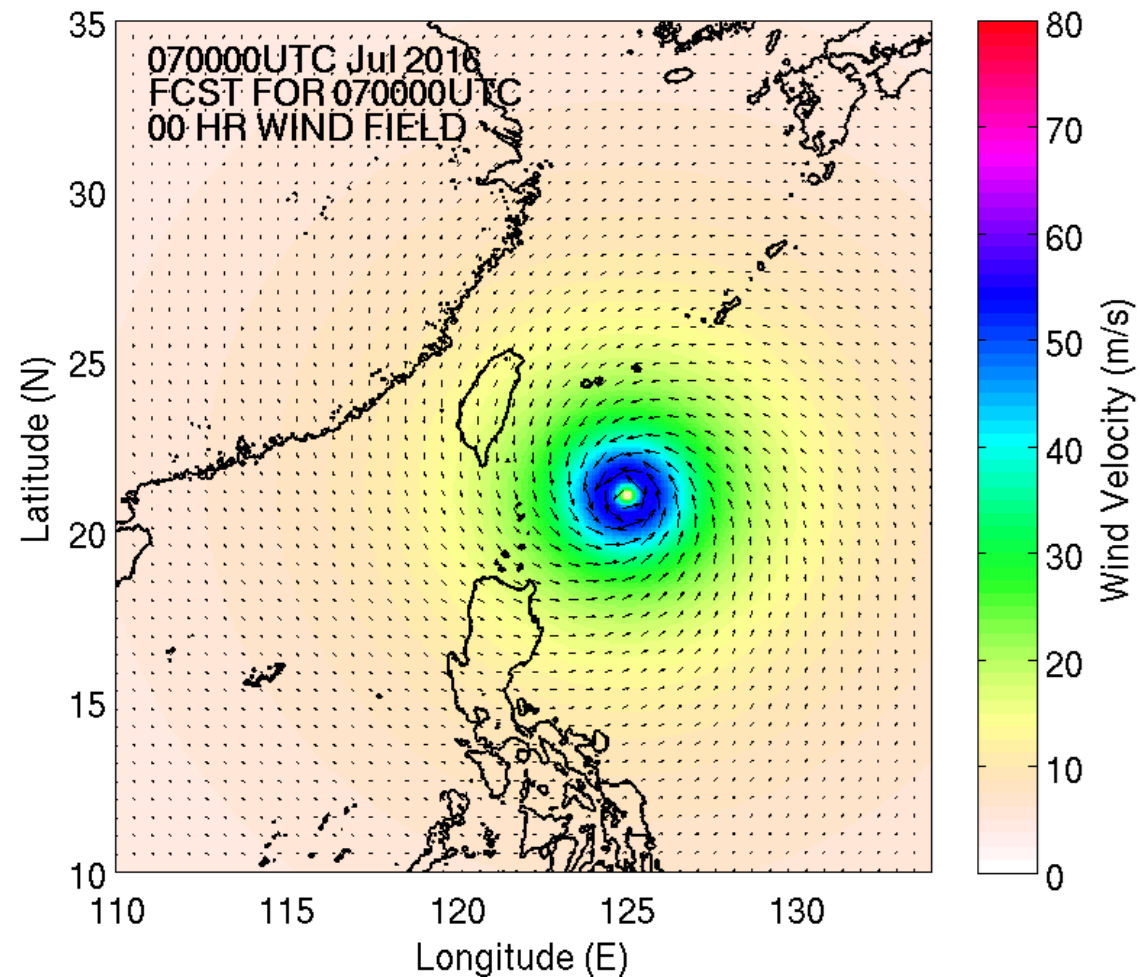


U.S Naval Research Laboratory

尼伯特颱風之氣象場

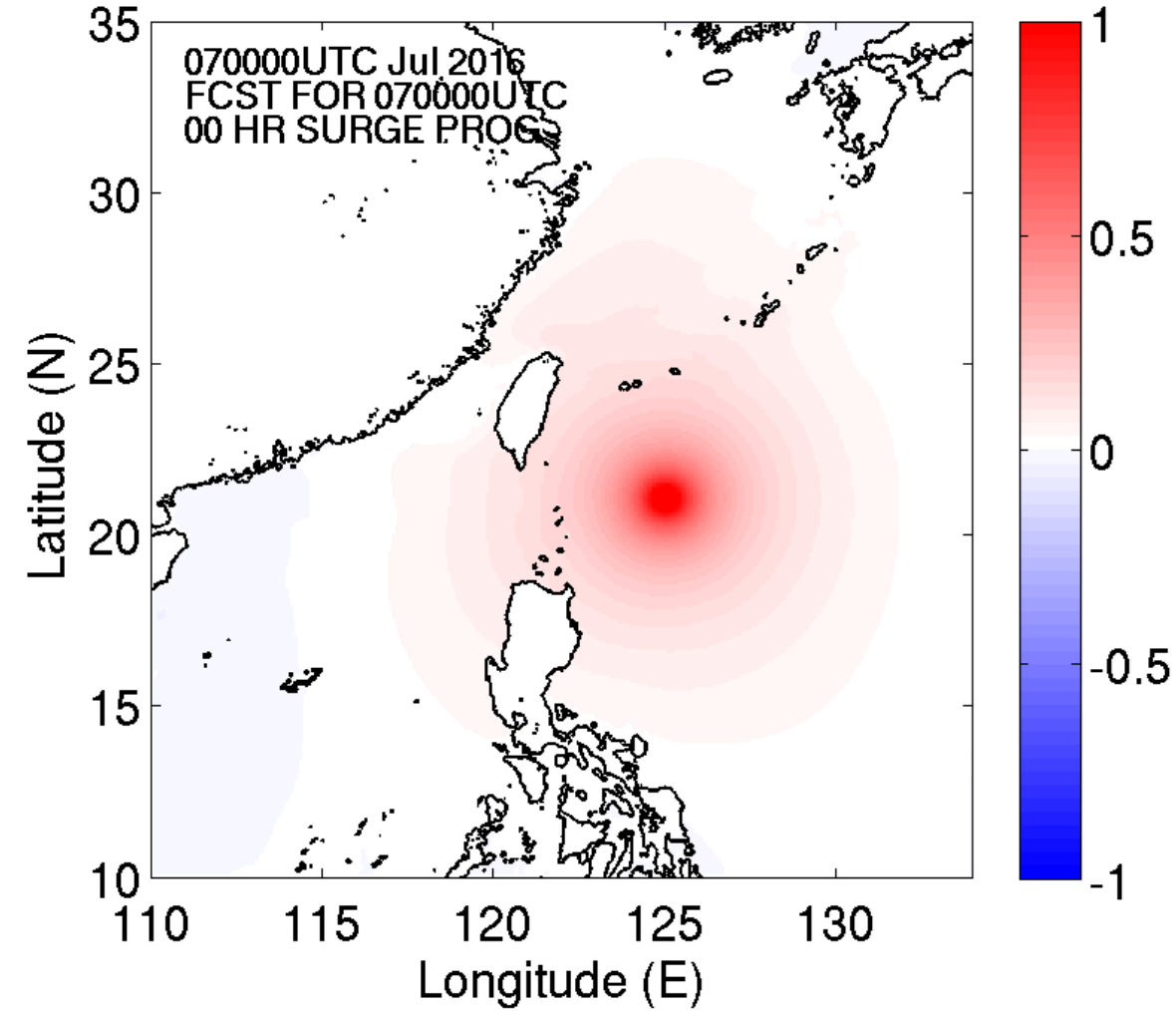


Pressure Field

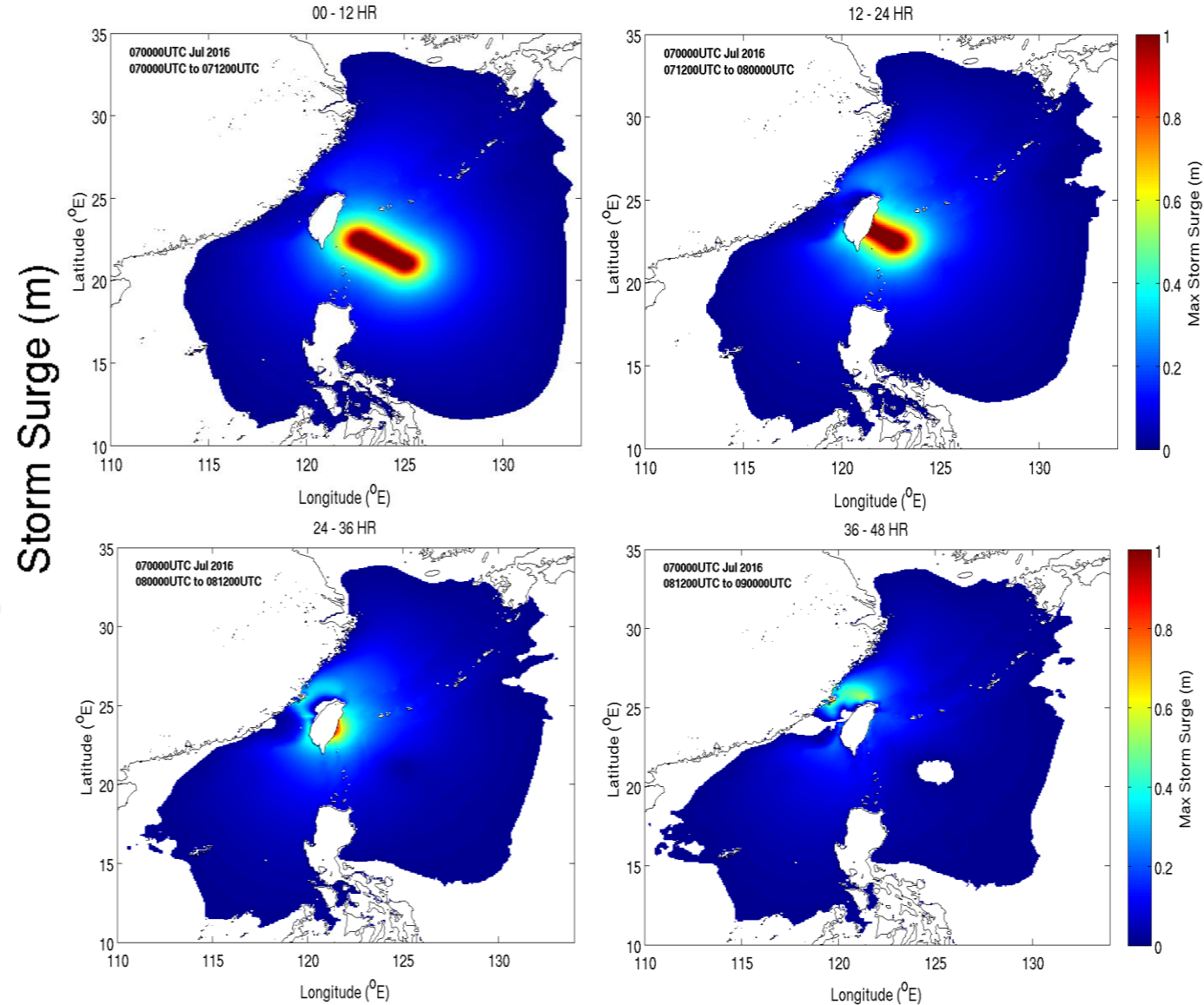


Wind Field

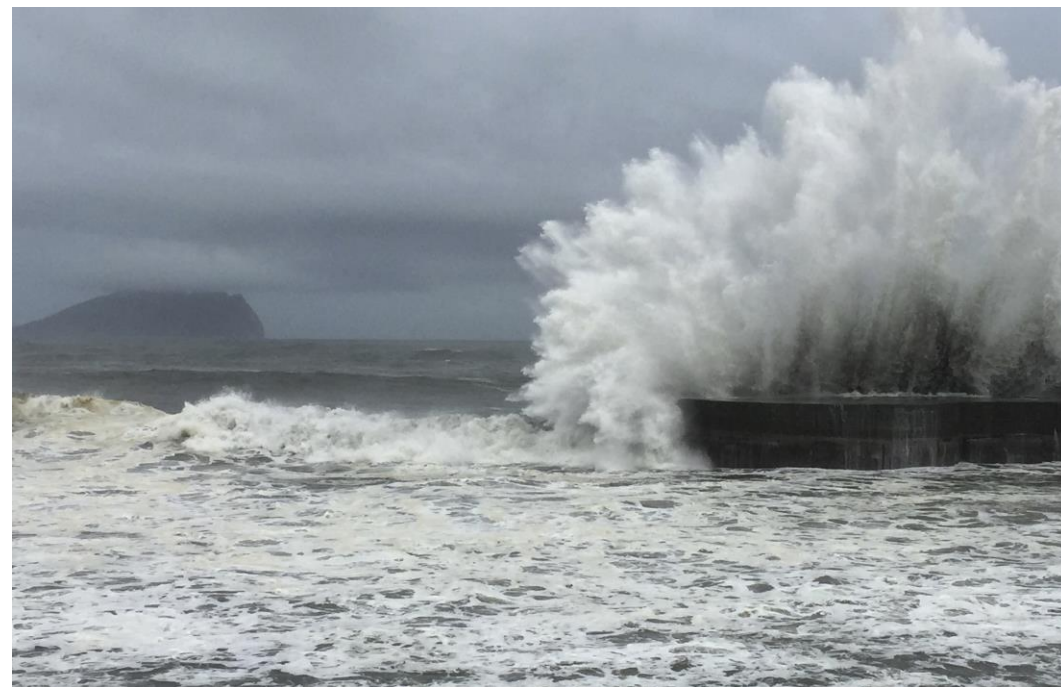
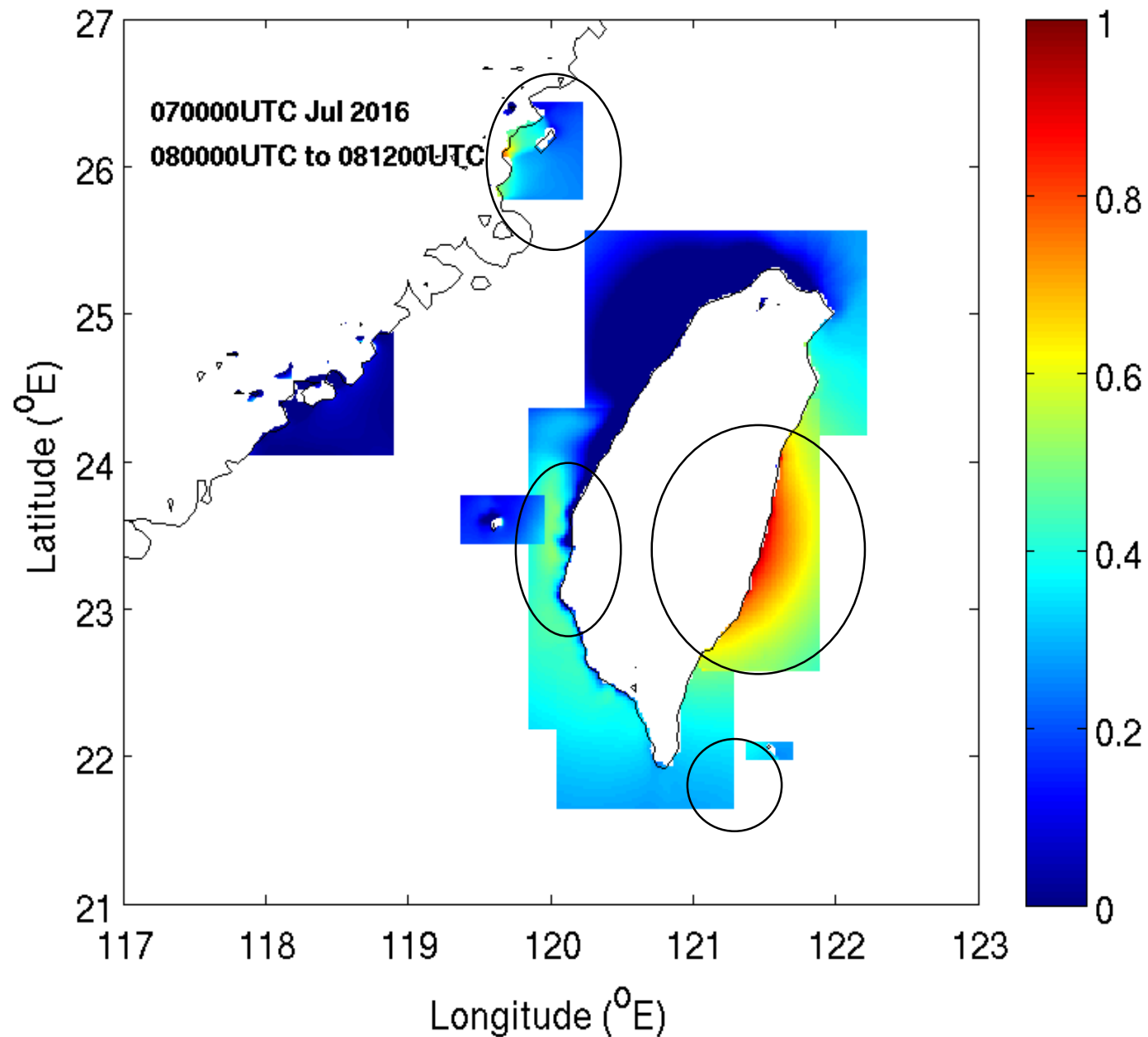
尼伯特颱風所誘發之風暴潮



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



Residual (24 - 36 HR)



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.

2016 Typhoon Meranti 颱風莫蘭蒂

今年地表最強 暴風圈今夜觸陸

風雨越晚越明顯

莫蘭蒂逢大潮 南台灣嚴防"暴潮"

壹電視新聞台

00:17 02:09

「馬勒卡」追兵在後 周末恐掃北台 莫蘭蒂「深夜觸陸」 花東高屏防豪下一則

讚 17萬 按「讚」加入壹電視Next TV FB粉絲團

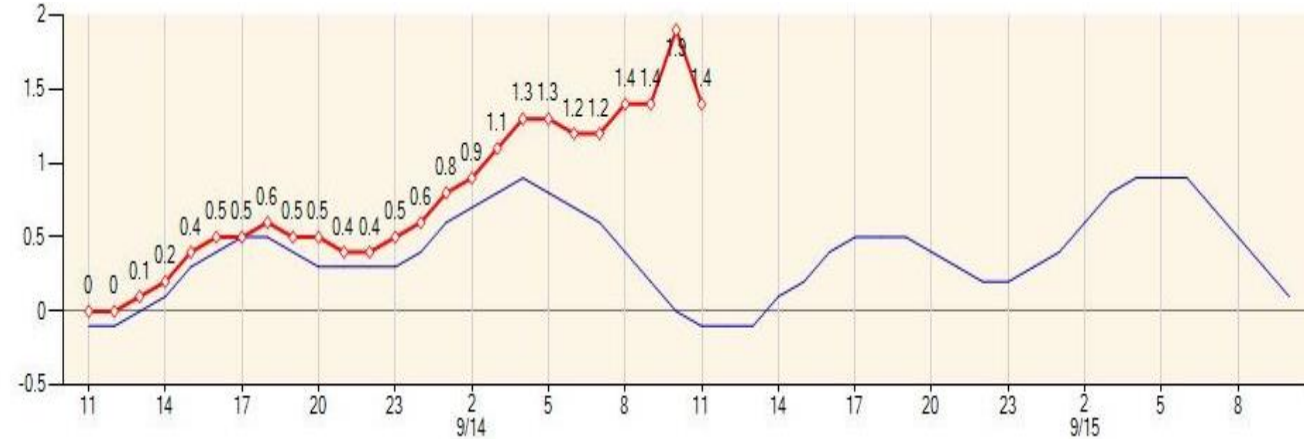
莫蘭蒂逢大潮 南台灣嚴防「暴潮」

2016-09-13 18:16 點閱：316

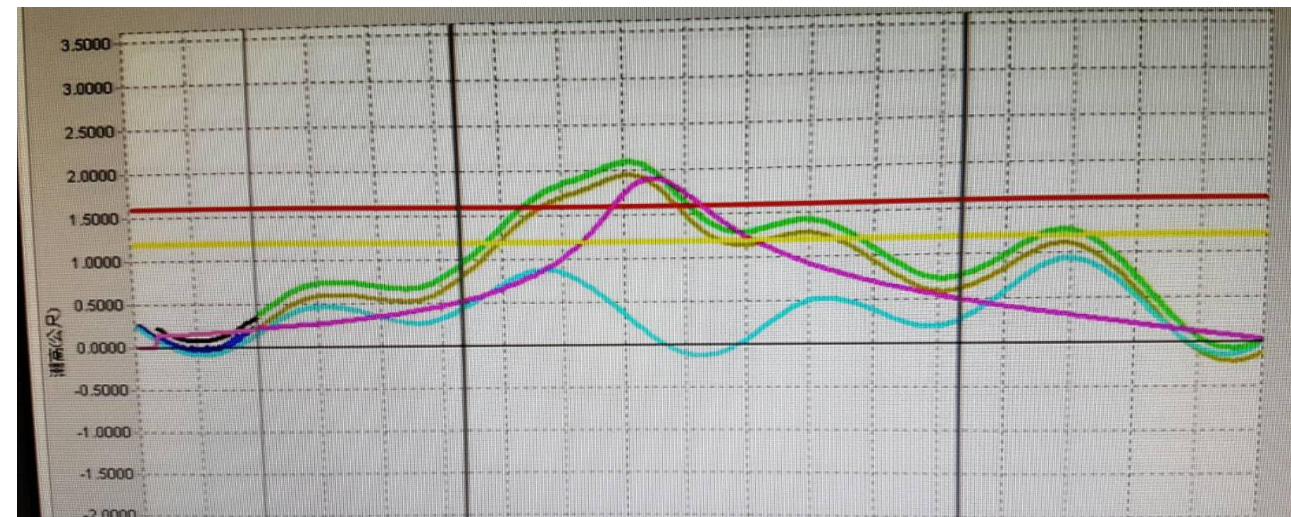
【壹電視報導】中秋節颱風來攪局，莫蘭蒂的路徑，還有驚人巧合，三年前，造成1.9億農損的強颱天兔，也是中心通過巴士海峽，除了暴風圈驚人，還加上適逢中秋節漲潮期間，大潮可能變暴潮，西南沿海東石到恆春，需要格外警覺！

The 1.9 m storm surge was observed at Southern Taiwan.

後壁湖潮位站



COMCOT Prediction



結果與討論

- 臺灣座落於世界上颱風最為密集且颱風強度最甚之區域，歷史上之災難性暴潮事件（例如：1845年雲林口湖暴潮事件）及近代之風暴潮災害記錄（例如：2015年杜鵑、2015年蘇迪勒以及2016年莫蘭蒂），均顯示臺灣區域曝露於潛在之風暴潮危害中，不可不慎。
- 澎湖縣島嶼眾多，地勢低窪，潮汐高低潮差可達2.5公尺以上，若風暴潮配合潮汐漲潮或滿潮時進入，所誘發之海水倒灌或海水溢淹，將對澎湖縣低窪地區造成莫大威脅。
- 風暴潮數值模式可協助颱風來臨前之暴潮警戒預報，或以過去歷史案例，分析潛在受風暴潮影響之區域，作為未來沿海區域規劃之用，預報資料和分析資料可作為鄉鎮市政府減災和防災目的之輔助工具。