ESCAP/WMO Typhoon Committee

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Roving Seminar 2016
Ha noi, Viet Nam, 15-17 / Nov / 2016

Phenomena of storm surges and its risk

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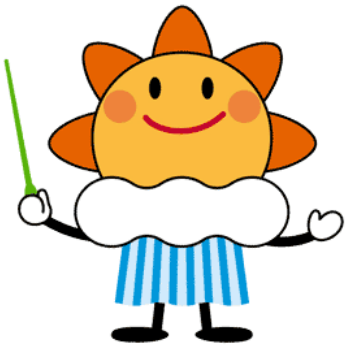
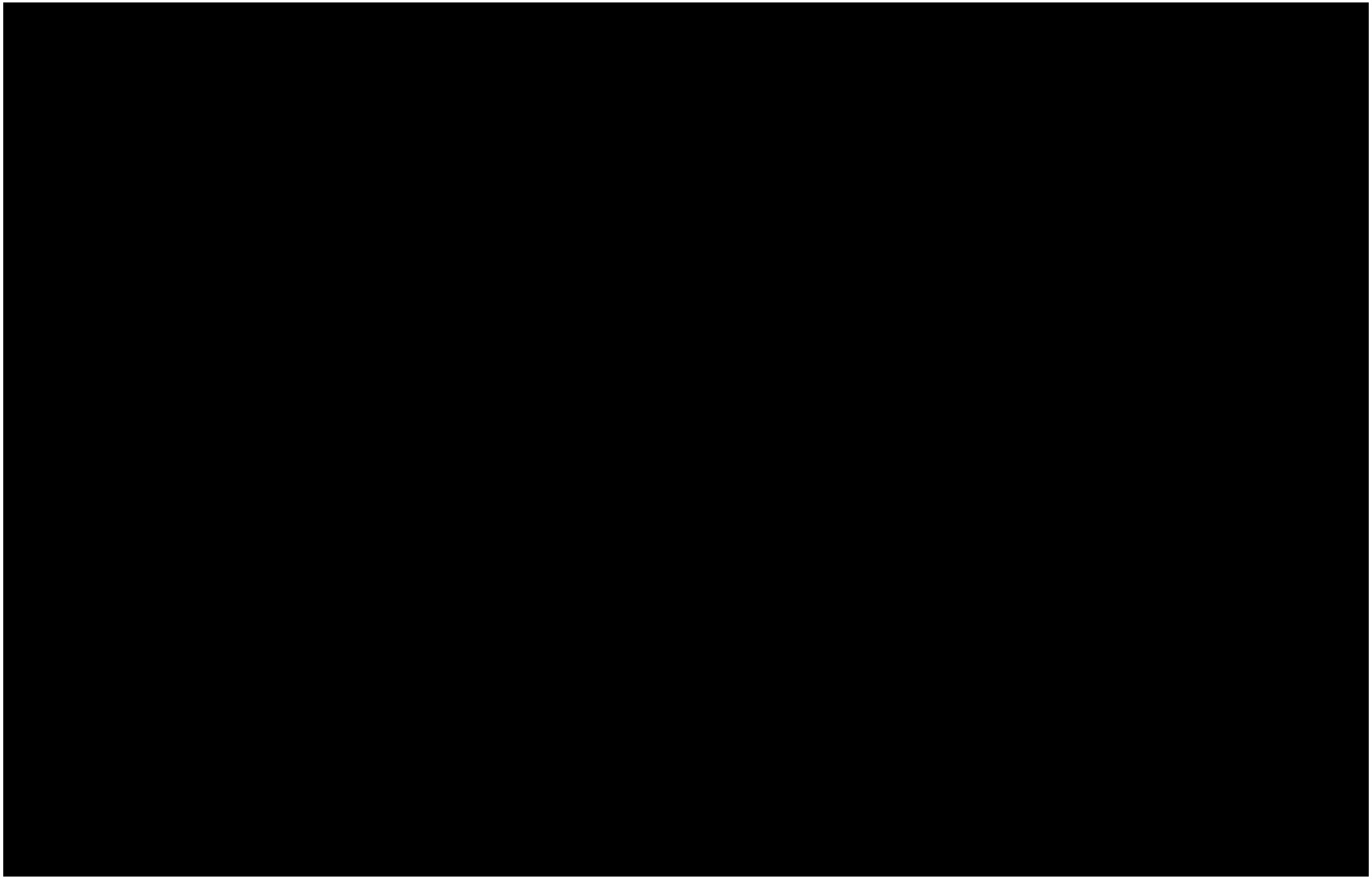


Storm surges by Hurricane Katrina(2005)



(UltimateChase.com)

Recent Storm surge disasters…

Although major storm surge events are rare, severe disasters by storm surges successively happened worldwide:

TC name	year	Max. Intensity	Economic loss (billion)	Fatalities	Typical storm surge
Katrina	2005	902hPa 135kt	$108	1,833	4-7m
Sidr	2007	944hPa 120kt	$1.7	~15,000	3-6m
Nargis	2008	962hPa 100kt	$10	138,366	3-5m
Sandy	2012	940hPa 95kt	$68	148 + 138	3-4m
Haiyan	2013	895hPa 125kt	$2.86	7,401<	5-7m

Storm surge disasters…

They are capable of causing significant disasters as measured by loss of life and critically damaged infrastructure.

Those storm surges brought about high death tolls and/or huge economic damages in the regions.

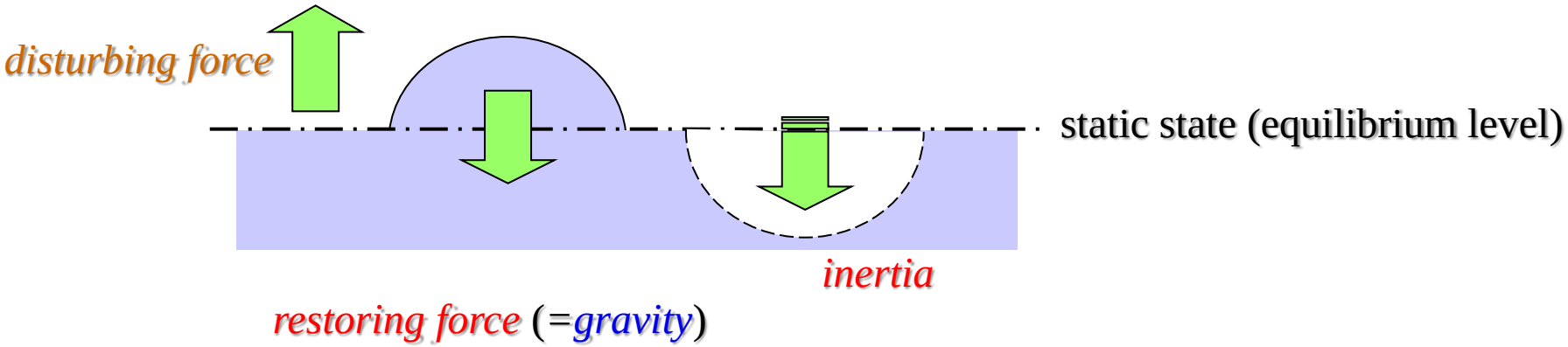
Therefore, storm surge is surely one of the key topics in disaster risk reduction.

Definition of storm surges

- Abnormal rise of sea level caused by meteorological phenomena (typhoons, hurricanes, cyclones, extra-tropical cyclones).
- Sea level changes are caused by strong winds and pressure depressions.
- From a hydro-dynamical point of view, storm surges are classified to **external gravity waves**, especially shallow water waves (long waves) as their large horizontal scale, as well as tsunamis.

Gravity waves

Wave motion: periodic motion around equilibrium line
disturbing force, restoring force, and inertia are necessary.



Gravity wave : the restoring force is ***the gravitational force***.

Comparison of storm surges, tsunamis and ocean waves

Cause is different

	Ocean waves	Storm surges	Tsunamis
Cause	Meteorological (strong) winds	Meteorological Strong winds and pressures (by TC etc)	Crustal movement (earthquakes, Eruptions)
Property of waves	Short wave (deep water)	Long wave (shallow water)	Long wave (shallow water)
Horizontal scales (m)	10^2	10^{5*}	$10^{5\sim6}$
Time scales (s)	10^1	$10^{3\sim5}$	$10^{3\sim5}$

Characteristics are different

*The horizontal scale of storm surges is assumed as TC scale.

(etymological trivia)

Tsu 津 (port)

nami 波 (waves)

: the waves become predominant and disastrous in ports

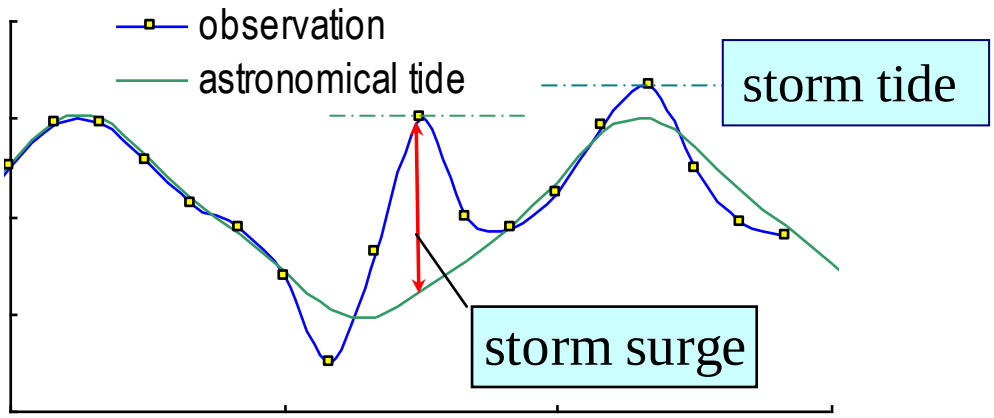
Expression of storm surges

- **Storm tide**

  Sea level including variation of astronomical tides.

  Storm tides are used for expression of the magnitude of disasters. Also used for disaster prevention practically.

  note: you need to be aware of the base water level, such as Mean Sea Level (MSL), Chart Datum Level (CDL) etc.



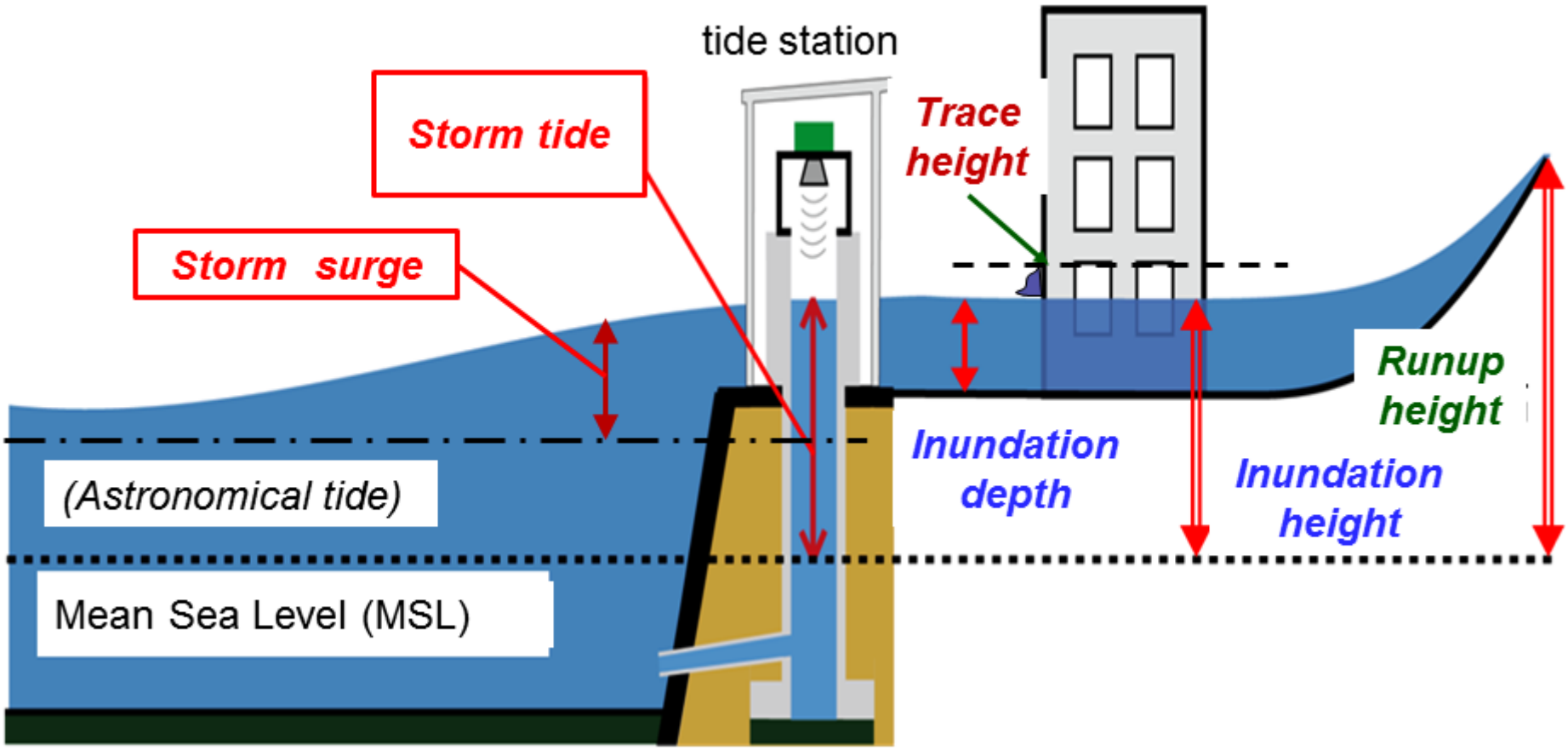
- **Storm surge**

  Sea level anomaly from (estimated) astronomical tide.

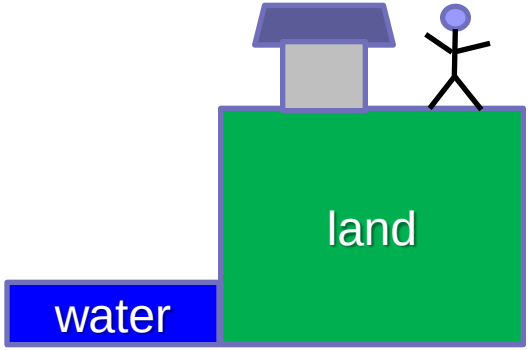
  Storm surges are used for expression of the magnitude of phenomena.

Strom surge ＝ observed sea level － astronomical tide

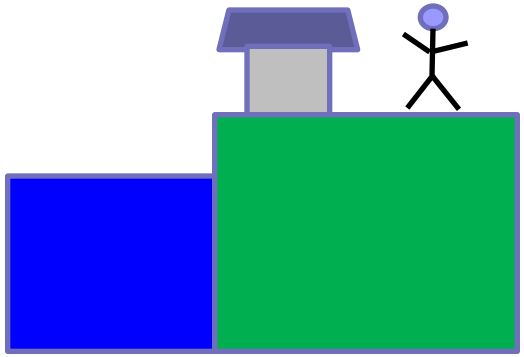
Terms related with storm surge and inundation



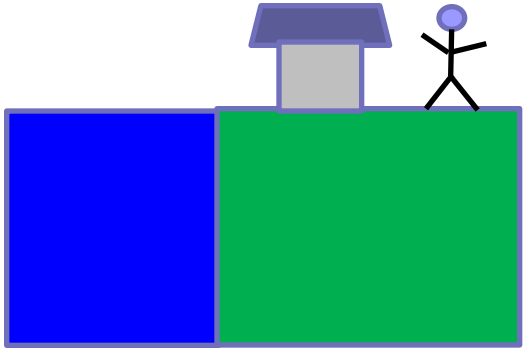
Risk of Storm Surges



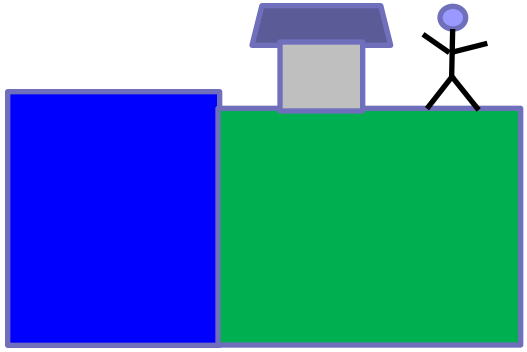
(definitely) Safe



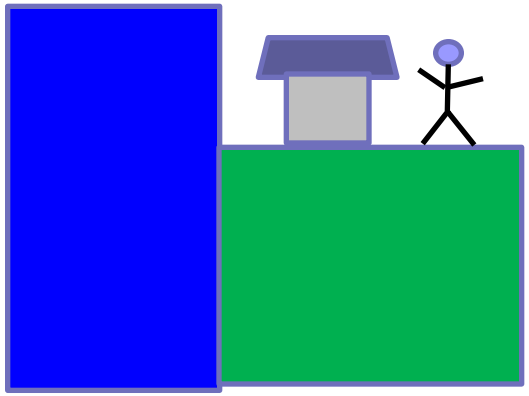
Safe



(still) Safe



danger

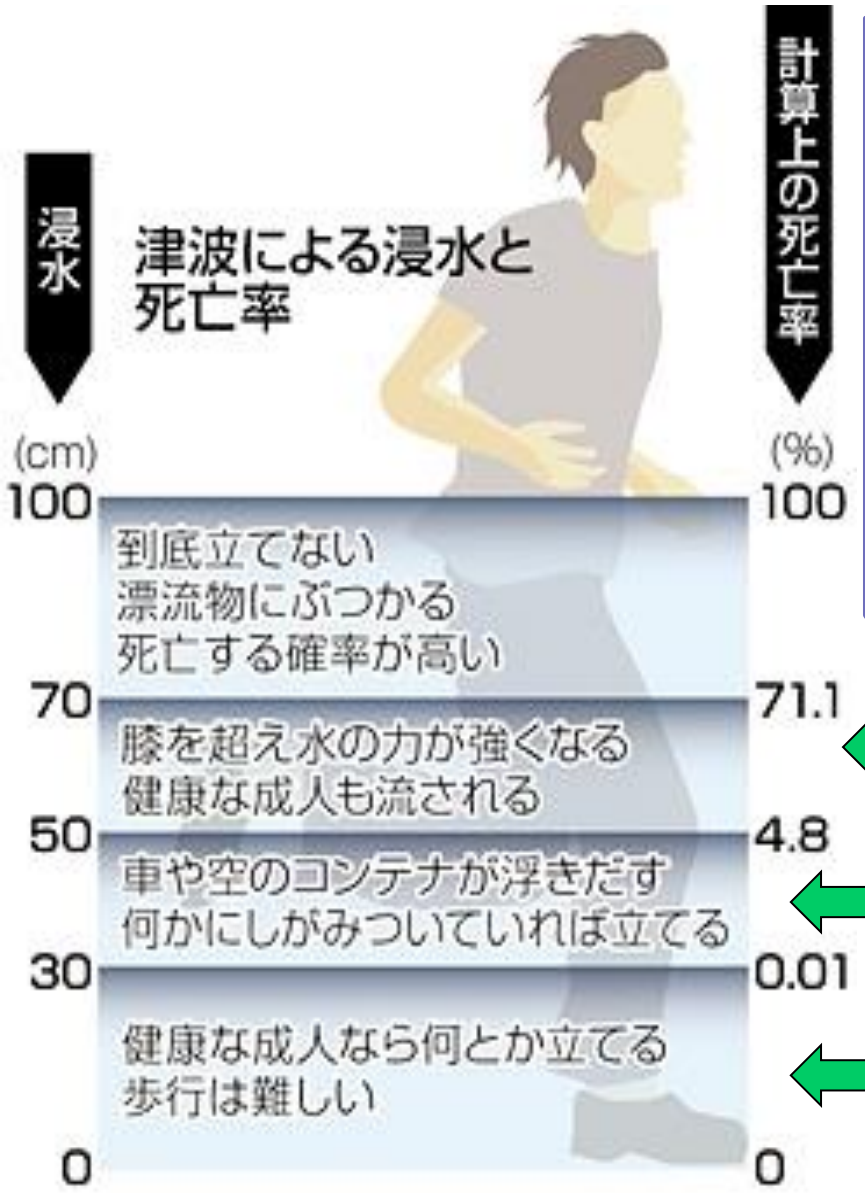


Very danger

Risk of storm surges is decided by the difference

Between water level and land height.

Dangerous Inundation



Inundation Depth

Estimated Death rate

A poster for tsunami inundation risk (Cabinet Office)

Impossible to stand
Floating obstacles hit
High possibility of death

Sturdy people will be washed down with strong water flow (higher than knees)

Cars/ empty containers become floating.
Can not stand without clinging to something.

Only healthy adults can keep standing, but are hard to walk.

Mechanism of storm surges

Storm surges

– caused by developed tropical cyclones etc.

What decides the magnitude?

a. Inverse Barometer effect

b. Wind set-up

a. Inverse Barometer effect

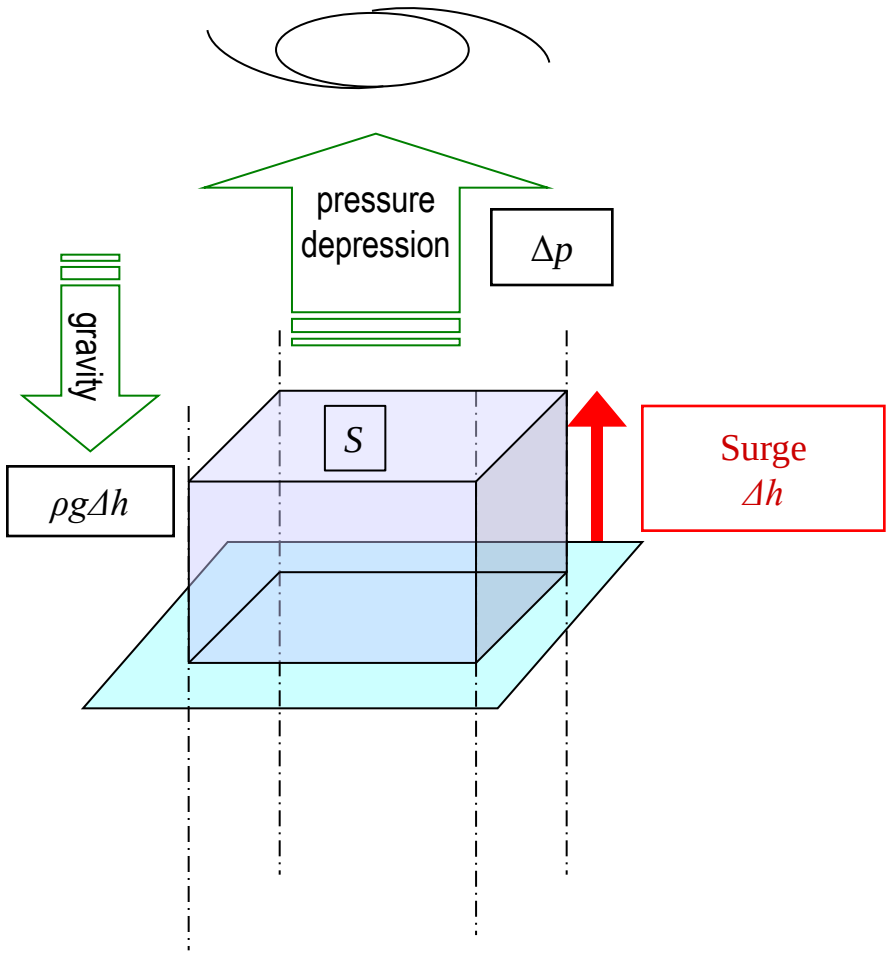
The static balance between sea level and surface pressure

ρ : sea water density
g : gravitational acceleration
S : area
Δh : sea level rise
Δp : pressure depression

$$g \cdot \rho \cdot \Delta h \cdot \cancel{S} = \Delta p \cdot \cancel{S}$$

$$\Delta h = \frac{\Delta p}{\rho g} = \frac{1.0[\mathrm{hPa}]}{1.0[\mathrm{g/cm^{-3}}] \times 9.8[\mathrm{m/s^{-2}}]} \cong 1.0[\mathrm{cm}]$$

1hPa pressure decrease
≒ 1cm sea level rise



b. Wind set-up

Wind force (Stress) to local water

τ : wind stress

L : fetch (horizontal scale)

h : water depth

$$g\frac{\partial \eta}{\partial x}\cdot\rho\cdot V\left(=\left(h+\eta+\frac{1}{2}\frac{\partial \eta}{\partial x}\right)\cdot W dx\right)=\tau\cdot W dx$$

$$\rho g\cdot\left(\left(h+\cancel{\eta}\right)\frac{\partial \eta}{\partial x}+\frac{1}{2}\cancel{\left(\frac{\partial \eta}{\partial x}\right)^2}\right)\cdot\cancel{W dx}=\tau\cdot\cancel{W dx}$$

$$\frac{\partial \eta}{\partial x}=\frac{\tau}{\rho g h}$$

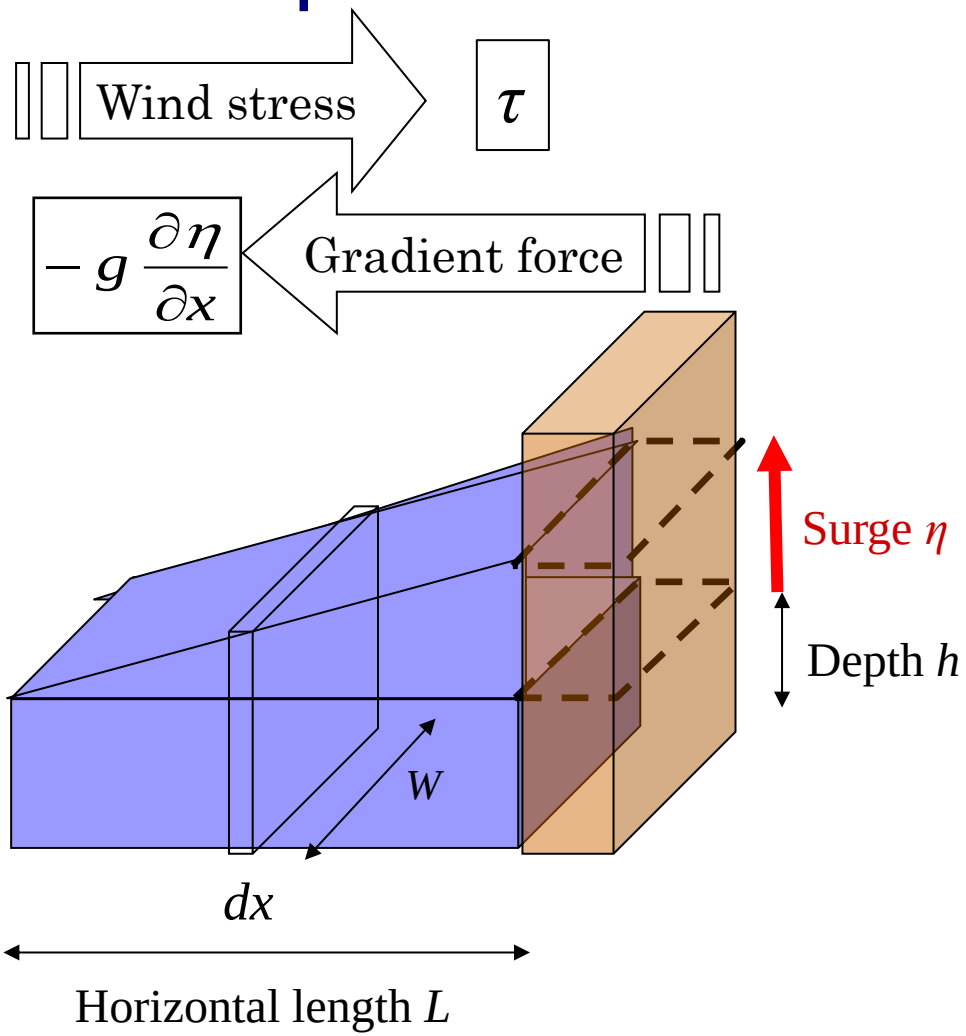
$$\eta=\int_0^L\frac{\tau}{\rho g h}dx=\frac{\tau}{\rho g h}\cdot L$$

η :

$\propto V^2$ ***(square of wind speed)***

$\propto L$ ***(horizontal scale of wind)***

$\propto 1/h$ **(inverse of water depth)**



Mechanism of storm surges

1. Inverse barometer effect

1hPa pressure decrease ≒ 1cm surge

$$\eta_p = \frac{\Delta P}{\rho g}$$

2. Wind setup

surge

$\propto \tau_s\,(V^2)$ (***wind stress: square of wind speed***)

$\propto L$ (***horizontal scale of wind: fetch***)

$\propto 1/h$ **(inverse of water depth)**

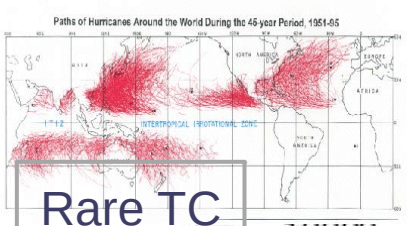
$$\eta_w = \frac{3}{2}\frac{\tau_s L}{\rho g h}$$

Geographic condition

Sea Bathymetry(GEBCO 30seconds)

The area vulnerable to storm surge

large storm surge



Rare TC

Mid-latitude lows

Tropical Cyclones

60˚ 90˚ 120˚ 150˚

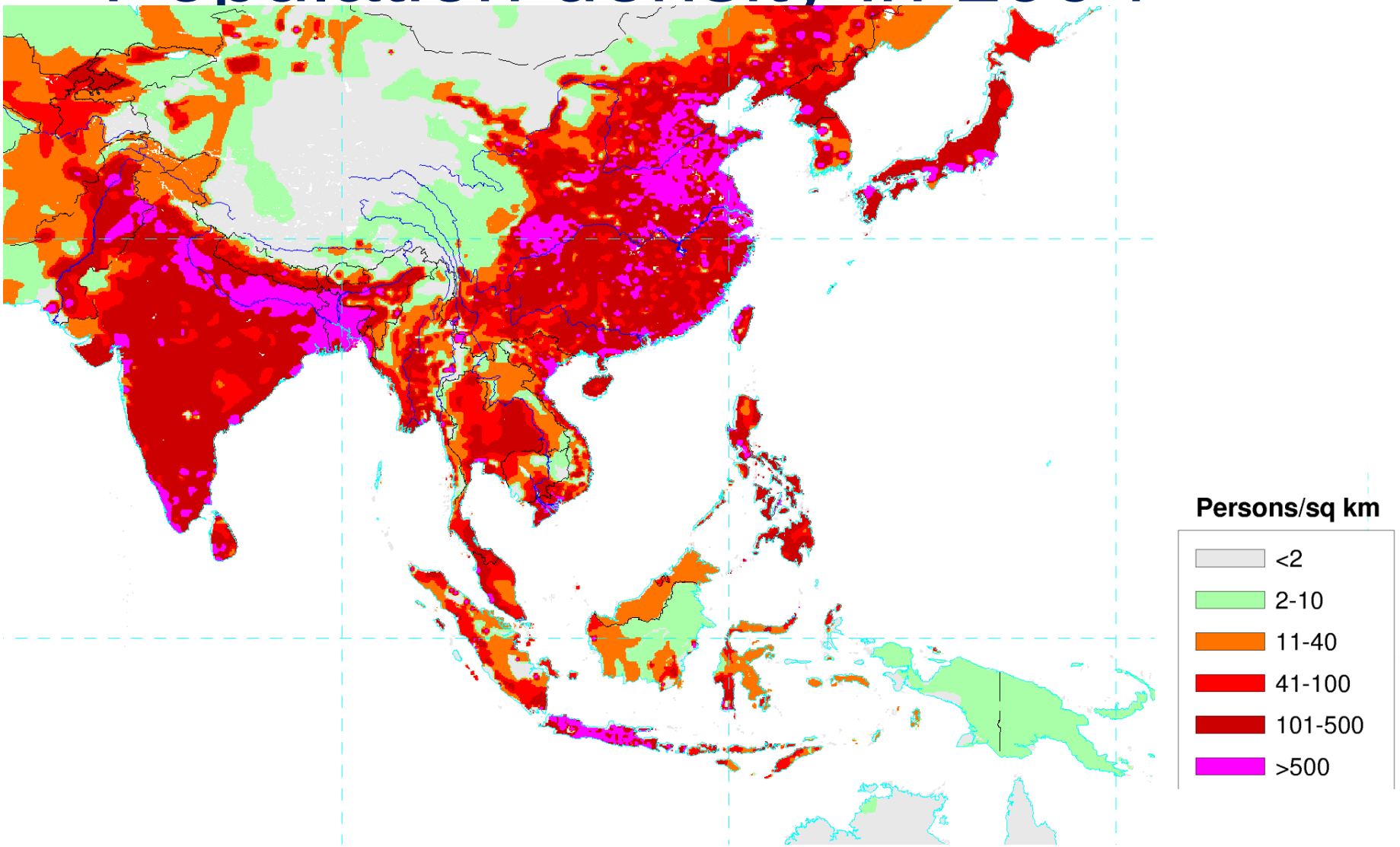
30˚ 0˚

m 10 5 0 -50

10000 9000 8000 7000 6000 5000 4000 3000 2000 1000 0 −1000 −2000 −3000 −4000 −5000 −6000 −7000 −8000 −9000 −10000

Contours are drawn in every 50m.

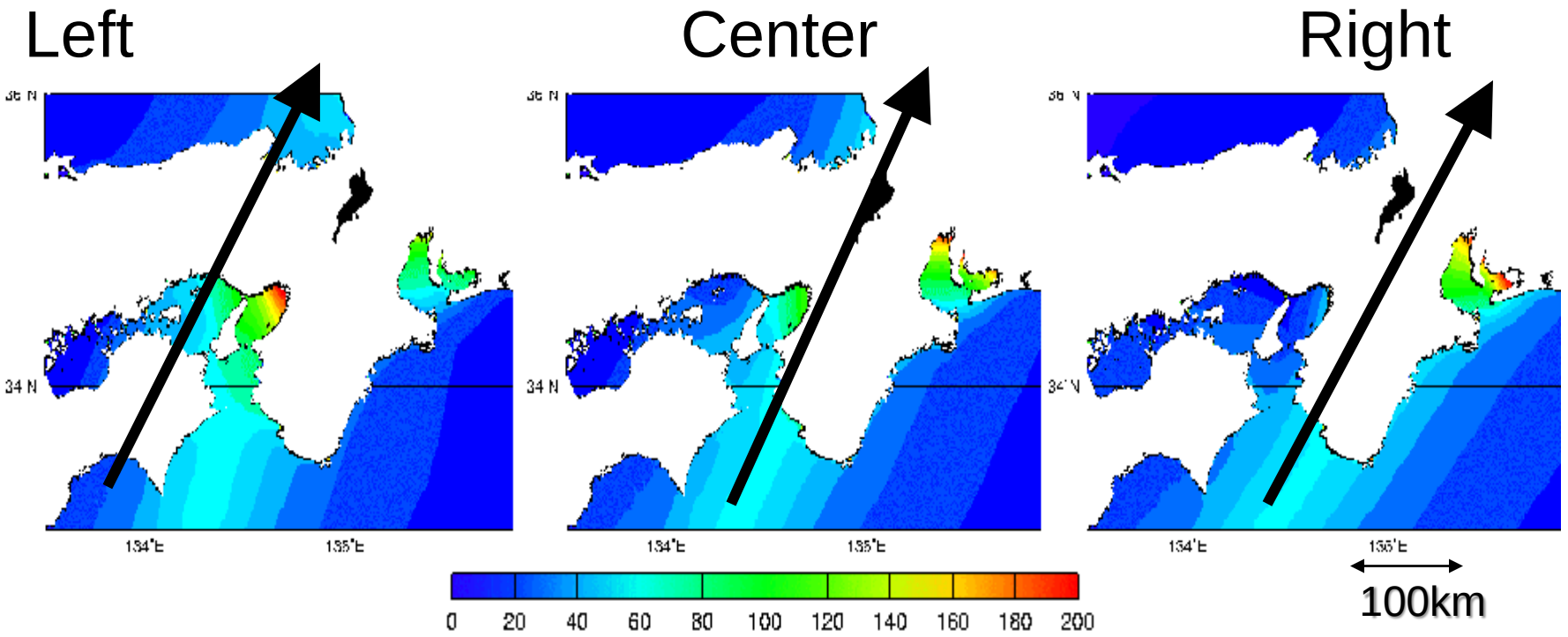
Population density in 1994



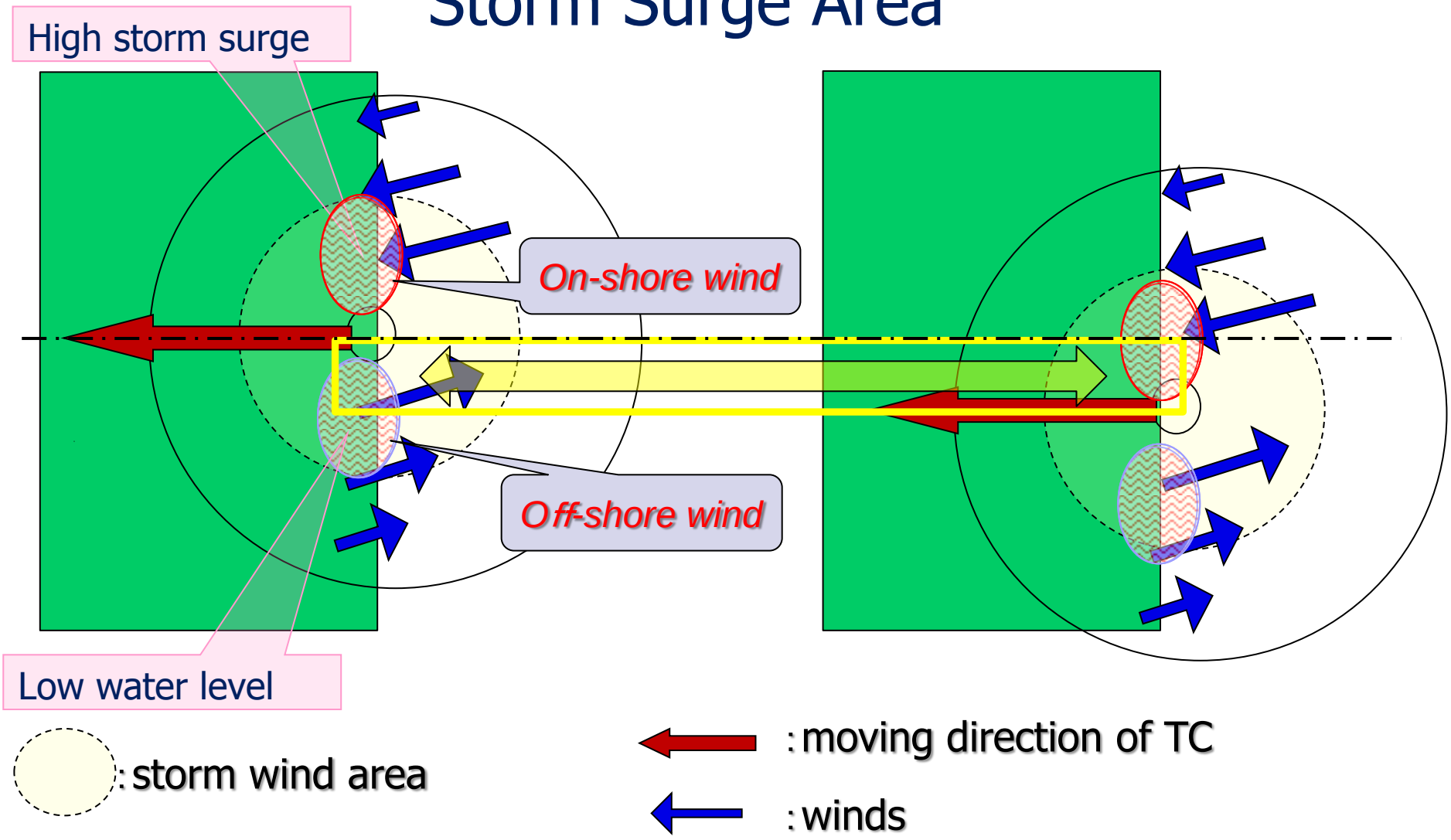
Recently many people come to live in low flat coasts.
Urbanization is one of main cause of heavy damage by storm surges.

Influence of typhoon track

Storm surges strongly depend on typhoon tracks.
Considering of track forecast errors, ***probabilistic approach*** would be practical.



Storm Surge Area



high storm surge area critically depends on

TC tracks (landfall point).

Another factors

- influence of astronomical tide
- Ocean wave effects（wave set-up, wave run-up）
- river flows

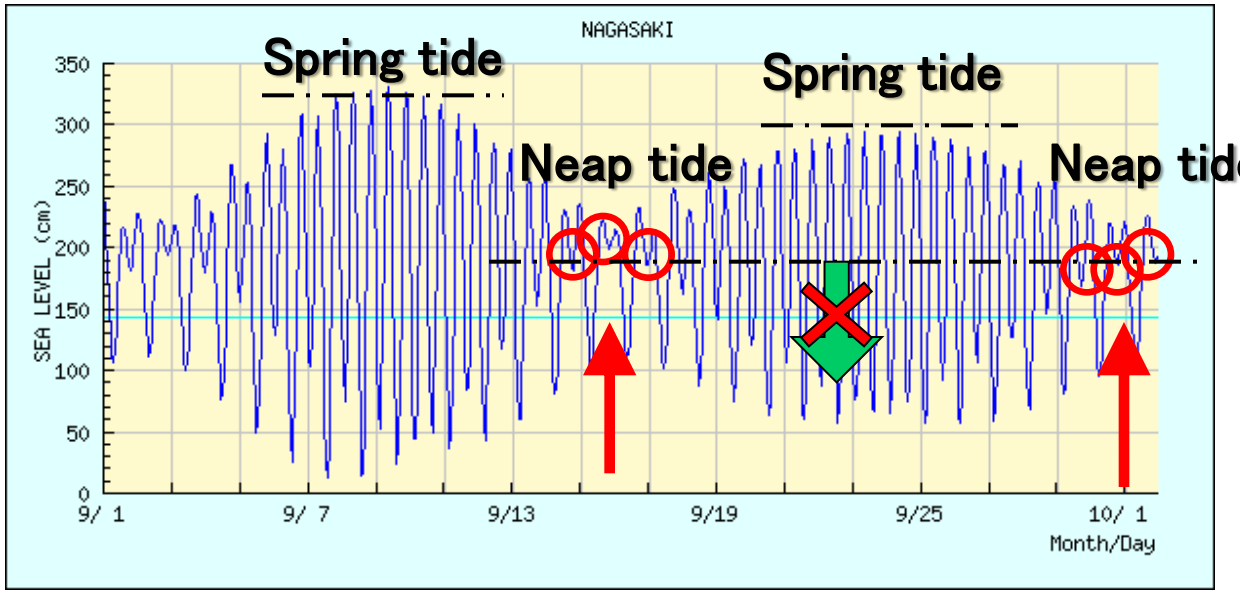
Influence of astronomical tide

- Storm tide

the high tide of the spring tide is dangerous

The low tide of the neap tide might be also notable

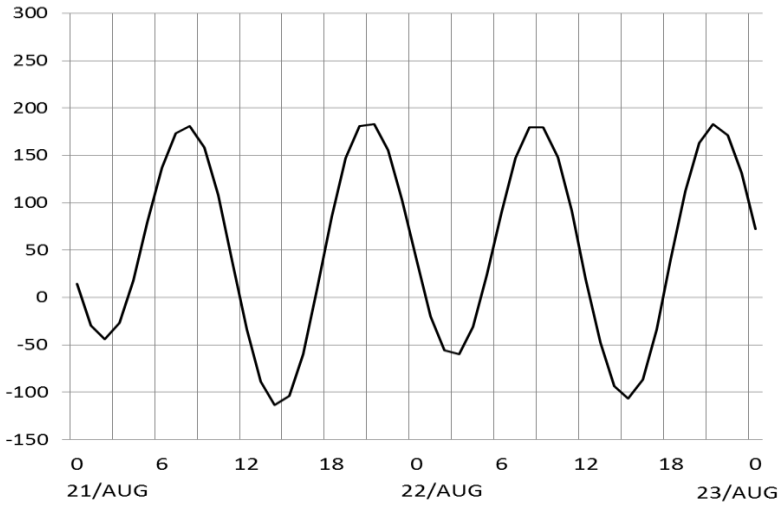
(water level does not so decrease in neap tide)



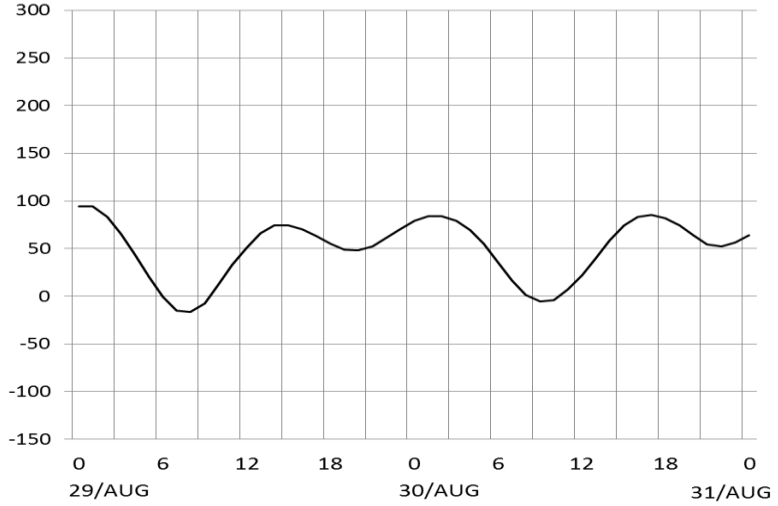
Astronomical Tides

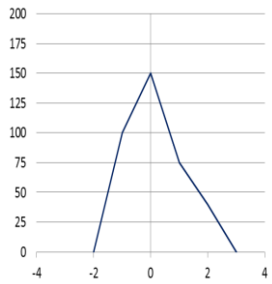
Assume that a typhoon hit and generated **maximum storm surge of 1.5 m**, in spring tide or neap tide.

spring tide



neap tide



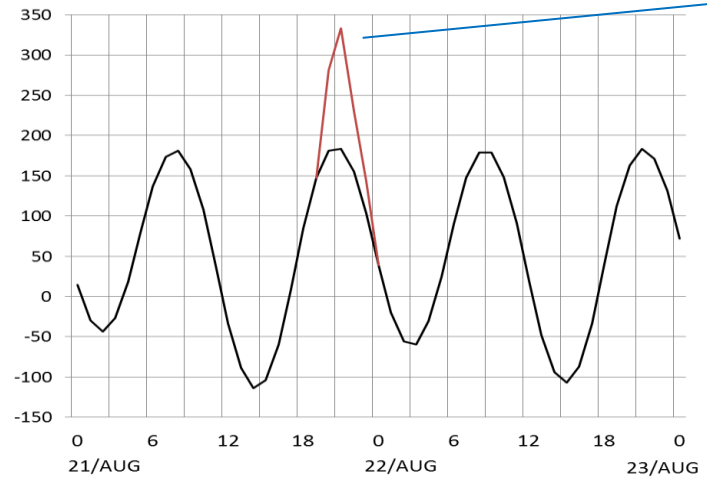


Storm surge

Storm tides

High tide + surge

In spring tide

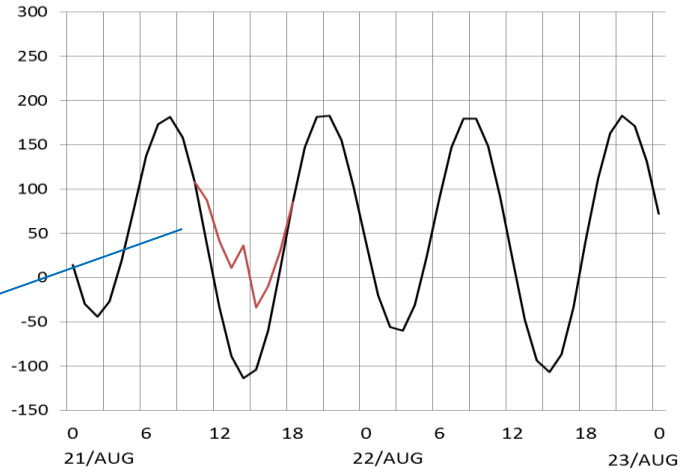


Tide : 1.8m
Storm Surge : 1.5m
Storm tide : **3.3m**

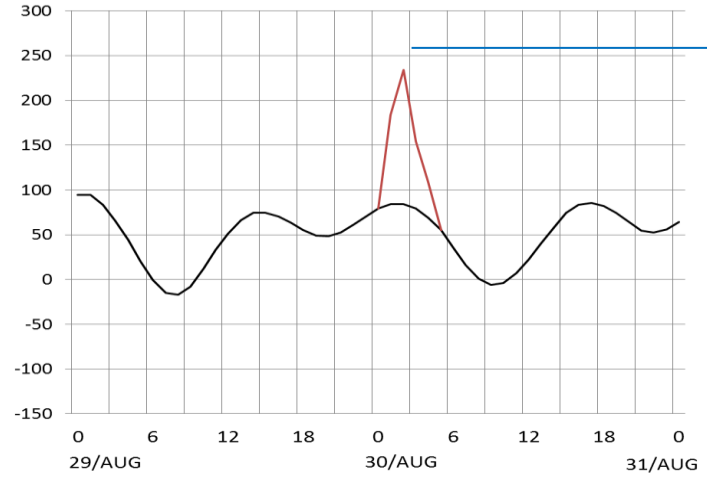
V
V

Tide : -1.1m
Storm Surge : 1.5m
Storm tide : **0.4m**

Low tide + surge

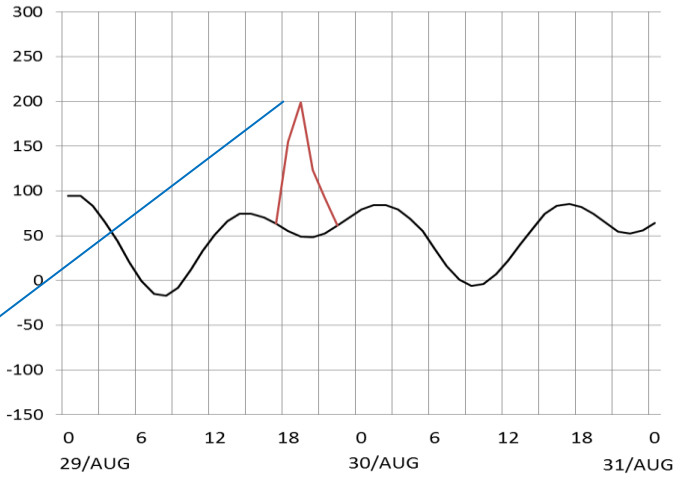


In neap tide



Tide : 0.8m
Storm Surge : 1.5m
Storm tide : **2.3m**

Tide : 0.5m
Storm Surge : 1.5m
Storm tide : **2.0m**



Tide + surge

- Strictly speaking, surge and tide are not separable and can not add linearly.
- However if tidal motion is small compared with surge, which is common in the case by tropical cyclones, the linear addition of storm surge and tide gives good estimation.

Wave setup

There are points where storm surge forecasts tend to be under-estimated.

Some of these points are likely to be influenced by the ocean waves (wave setup).

When wave setup becomes predominant?

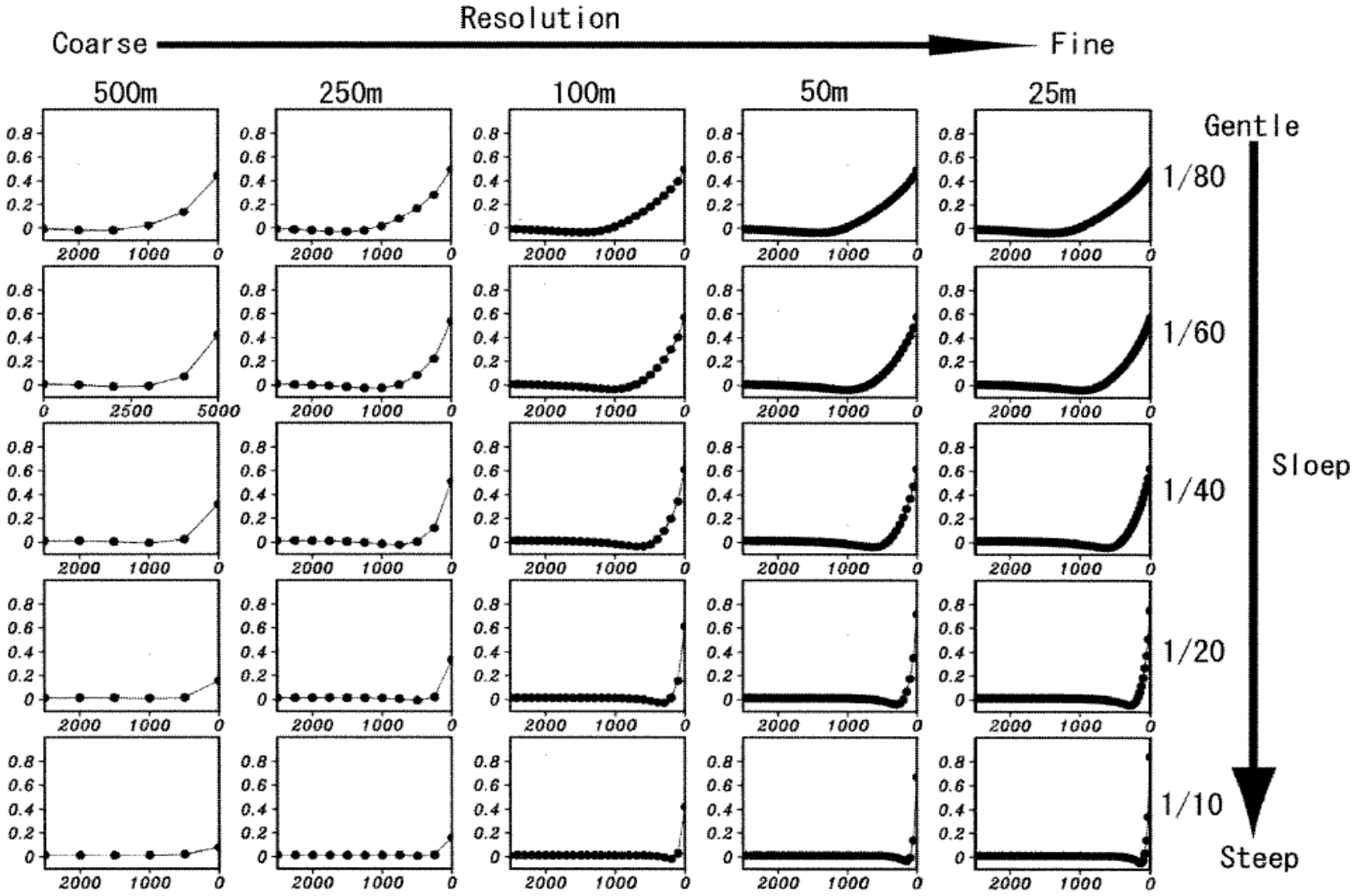
- High waves hit to the coast
- Water depth quickly becomes shallow near the beach

wave setup ~ 0.1 – 0.2 Hw

The mechanism was explained by Longuet-Higgins and Stewart (1962).

However, the effect is not included in the operational forecast models, because it needs very high resolution for accurate wave setup calculation.

Wave setup sensitivity

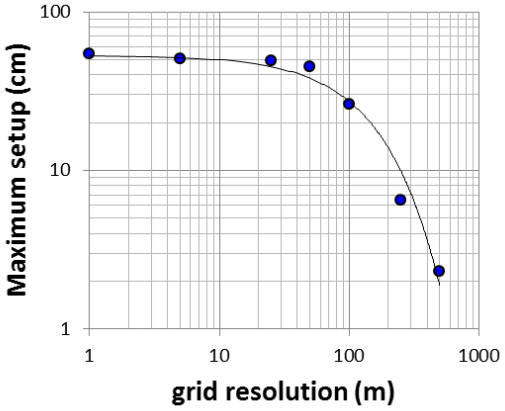


Sasaki and Iizuka (2007)

Wave setup model

For operational use, a simple wave setup estimation model based on Goda (1975) was developed (Now the model is in further modified).

- ✓ The offshore wave: Operational wave model predictions
- ✓ The model estimates wave height (energy) changes in surf zone (considering of water depth change and so on)
- ✓ Wave setup values are calculated from the estimated wave.

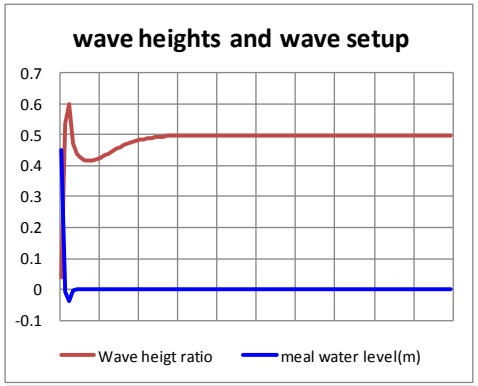


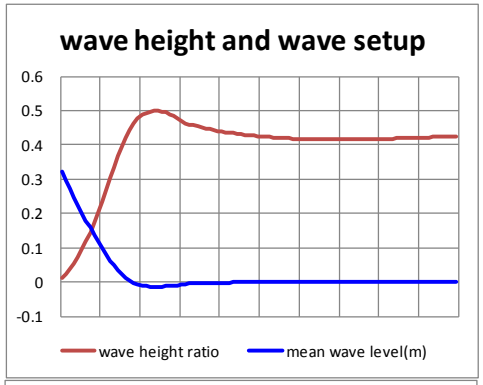
Sea topography gradient: 1/10 1/100 1/1000

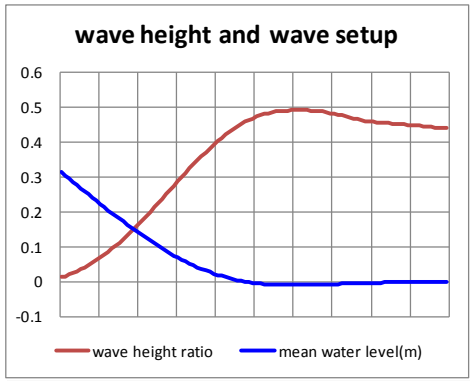
Input (offshore wave)

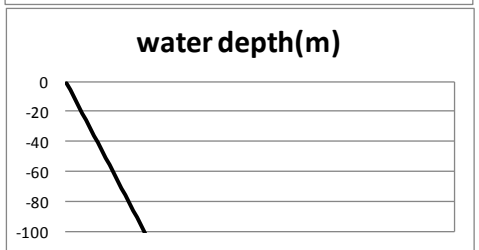
Hw= 6.0m, Tp=12 sec

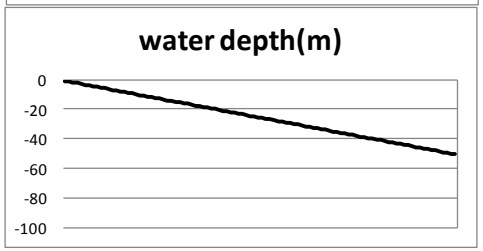
- constant gradient
- grid resolution
  50m (1/10 and 1/100)
  200m (1/1000)

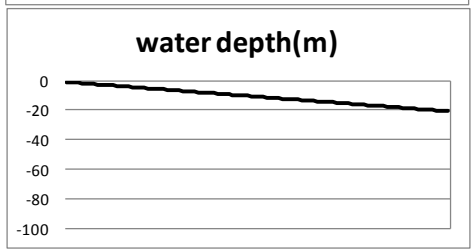






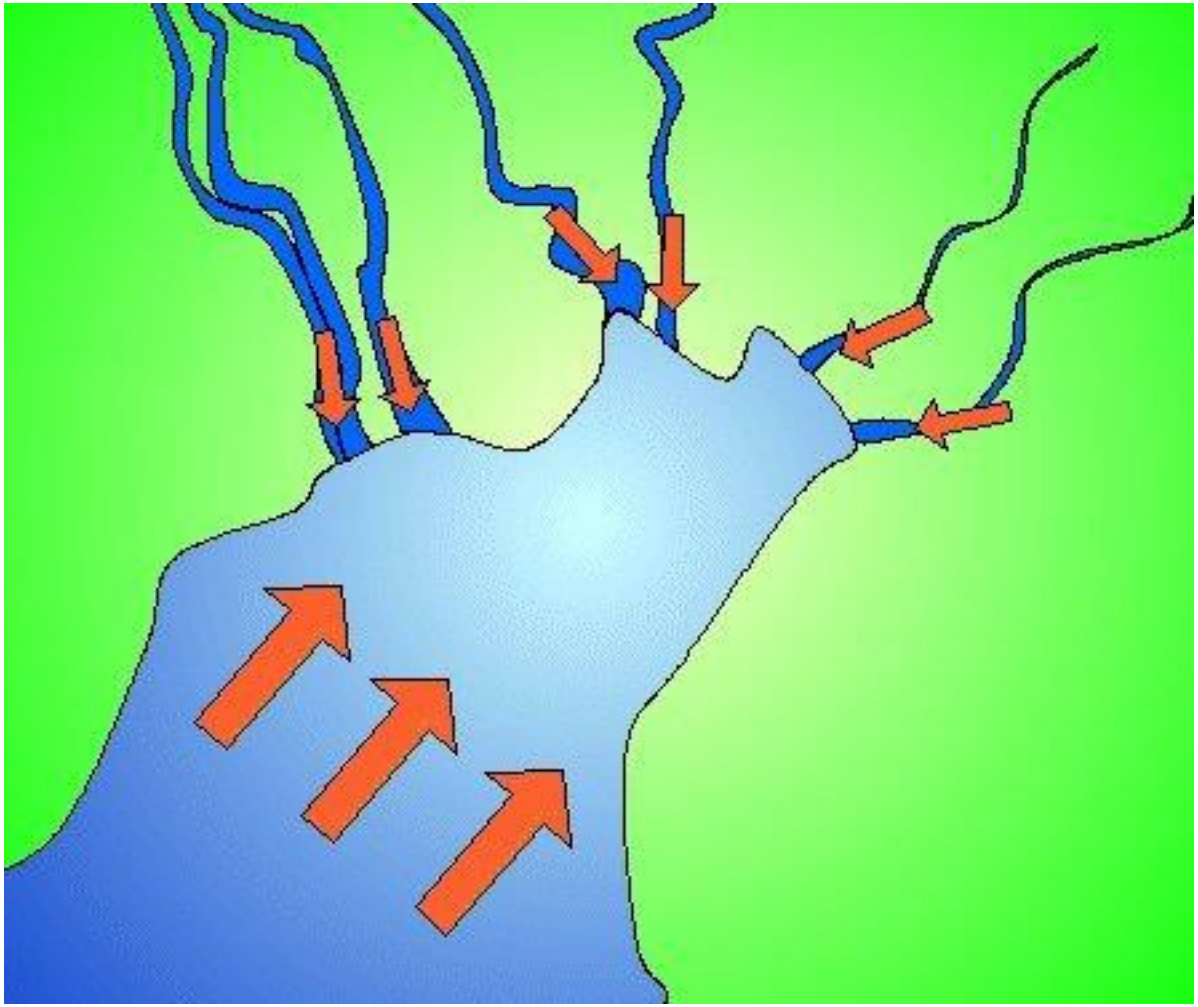






river flows

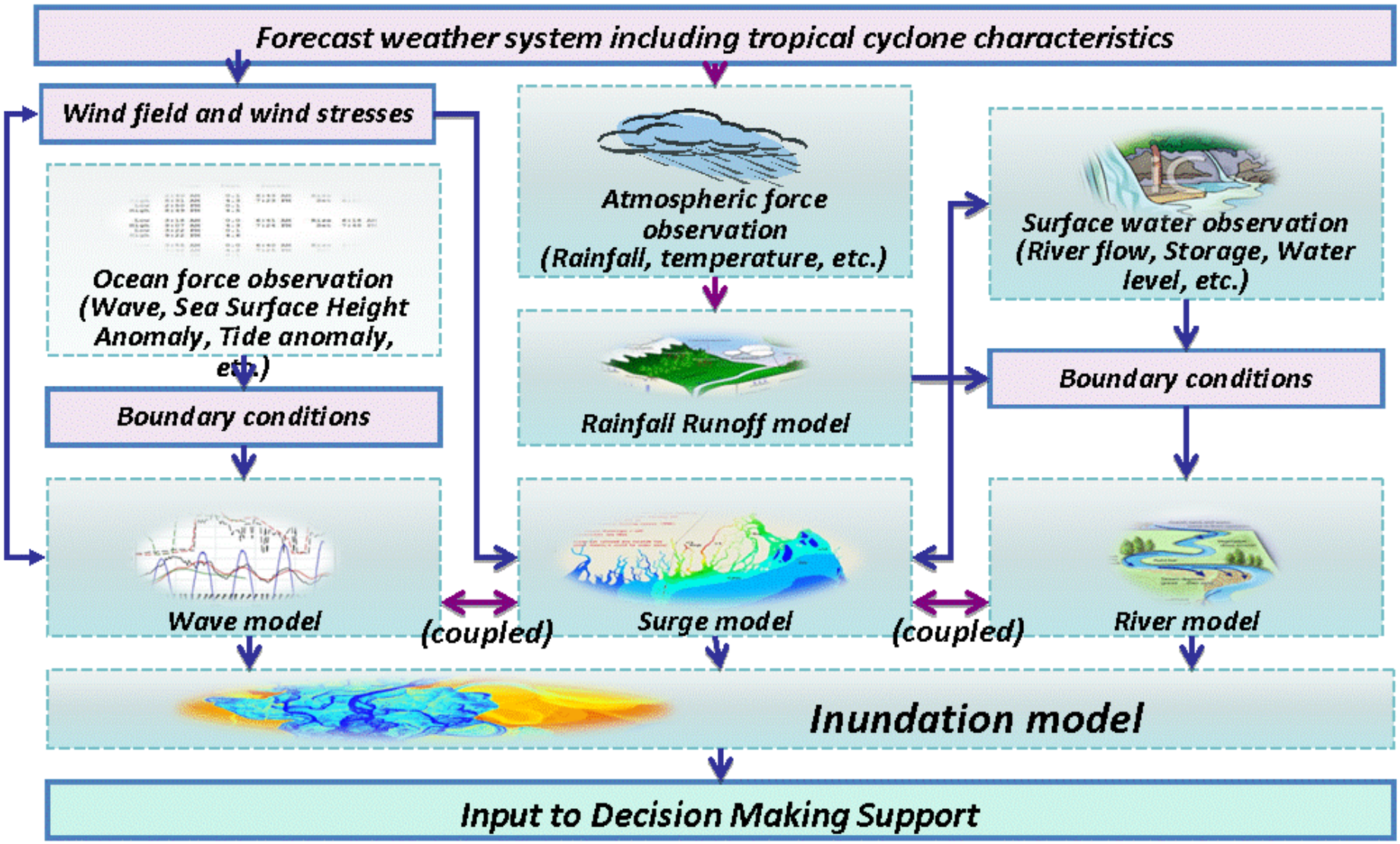
In estuary part, river flow also enlarges surges



In current status, it is difficult to estimate the interaction between storm surges and river flows, especially in operational purpose.

Therefore we need to keep in mind that such effects may happen and to issue warnings being afraid of the worst cases.

CIFDP: Technical Development for Coastal Inundation Forecasting/Warning



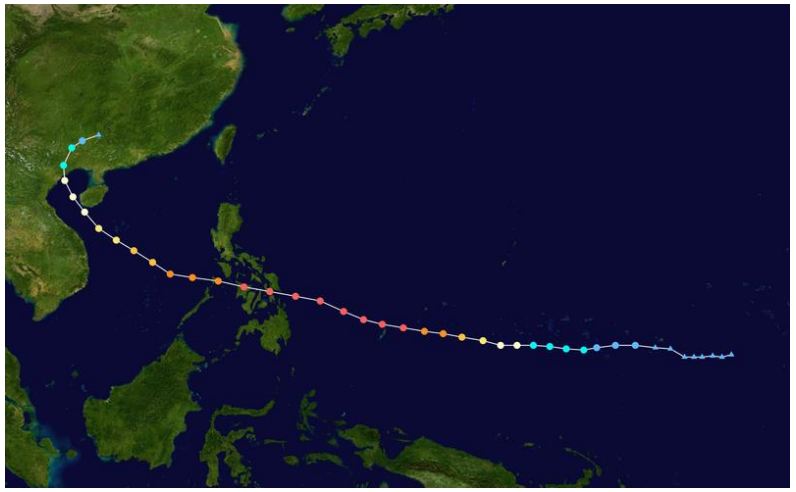
Case studies

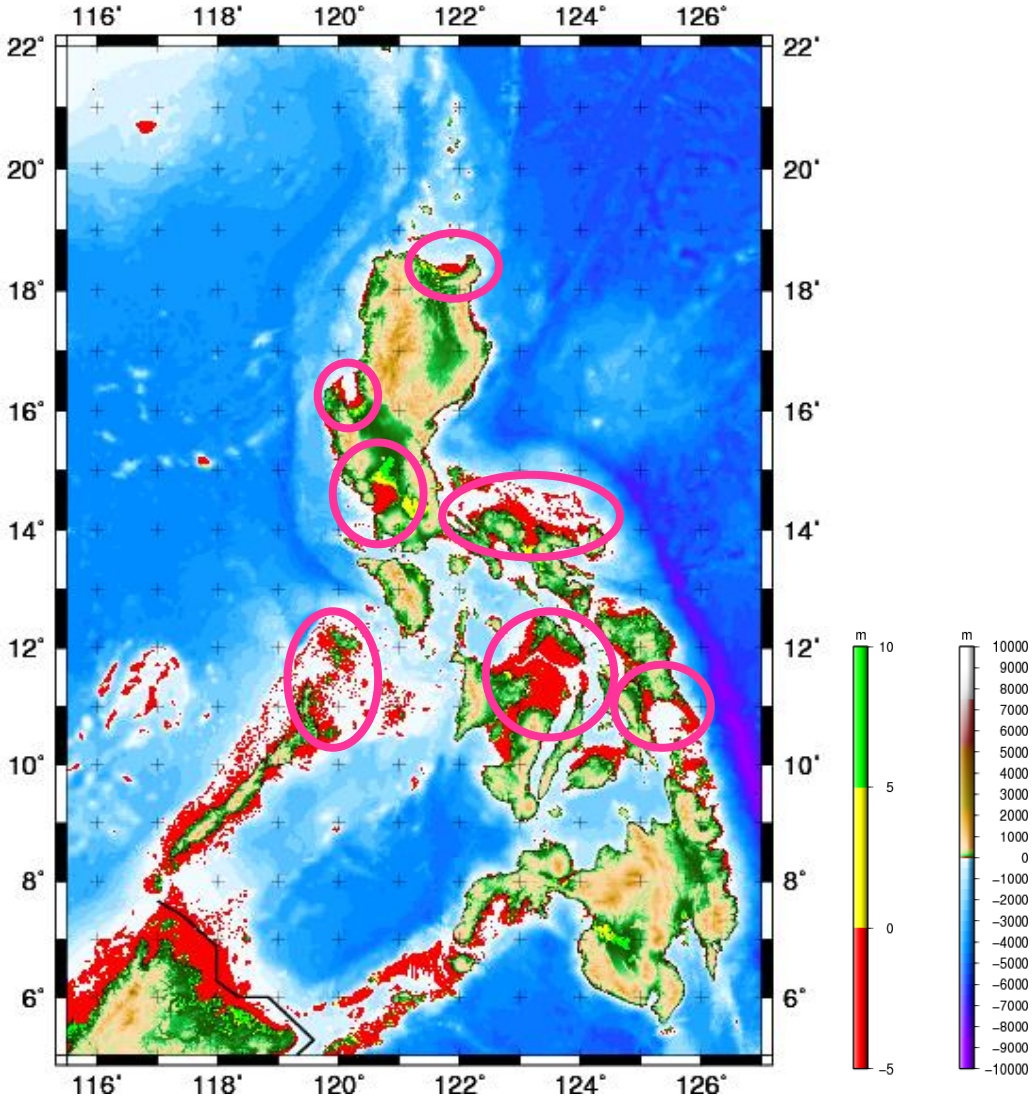
- Typhoon Haiyan in 2013
  - large storm surge in the Philippines

Storm surges by Typhoon Haiyan (1330)

Provided by Mr. Renito B. Paciente (PAGASA)

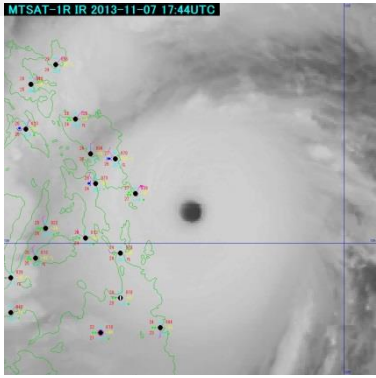
Storm surges by Typhoon Haiyan (1330)





Bathymetry of the Philippines

Operational Analysis



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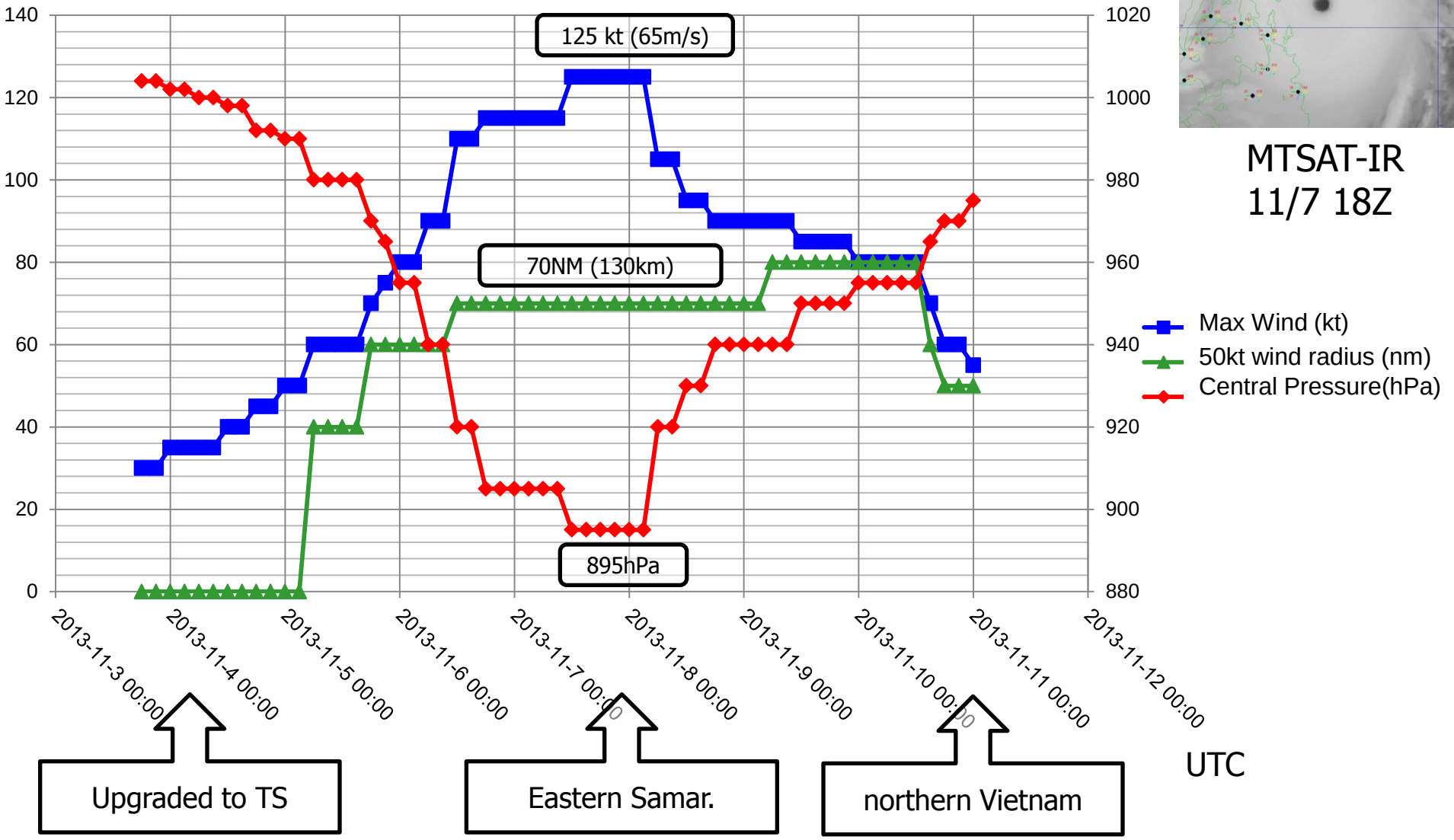
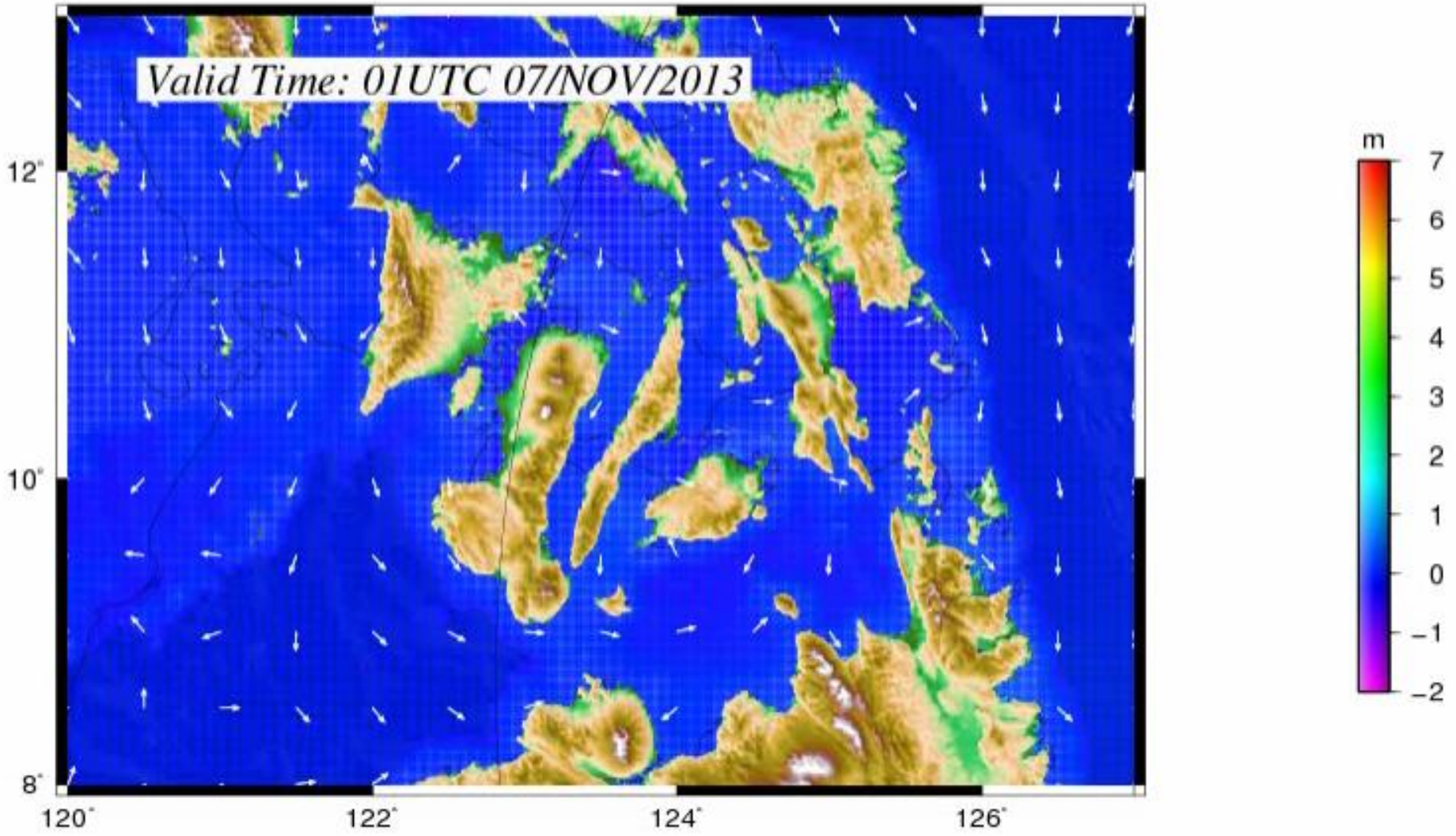


Upgraded to TS

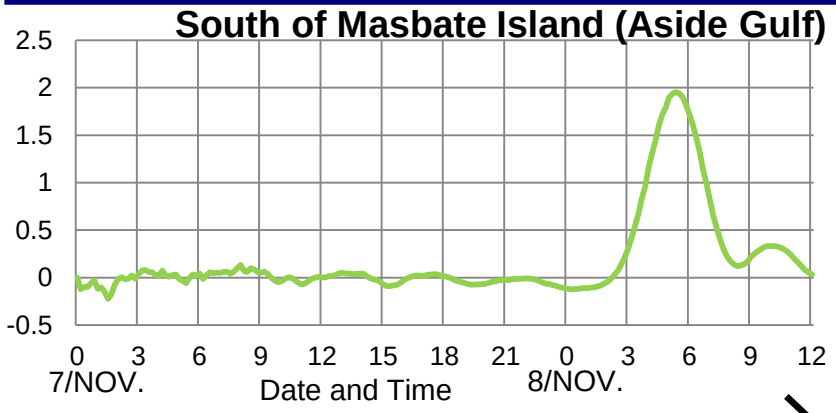
Eastern Samar.

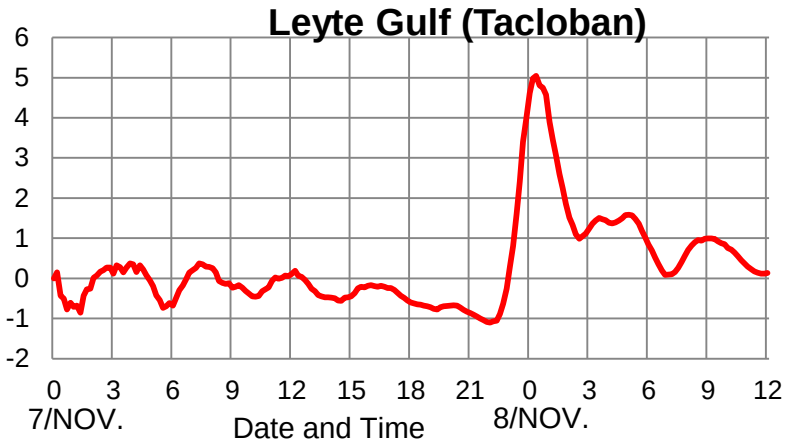
northern Vietnam

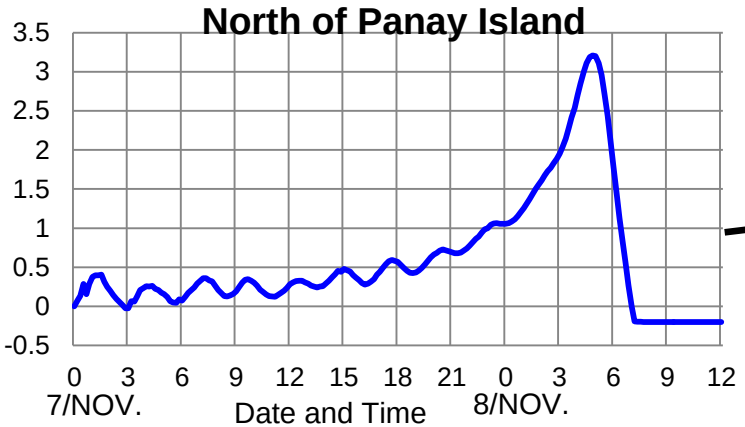
Storm Surges in Philippines by Ty Haiyan

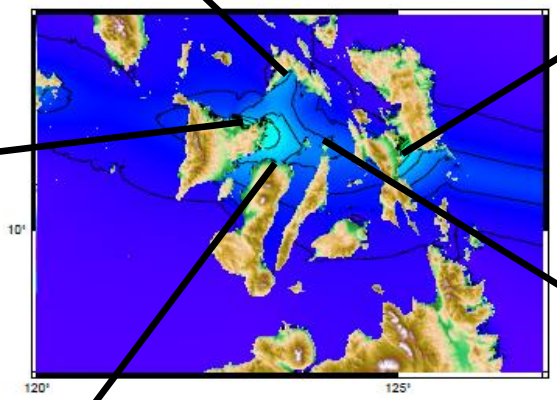


Storm surges by Ty Haiyan

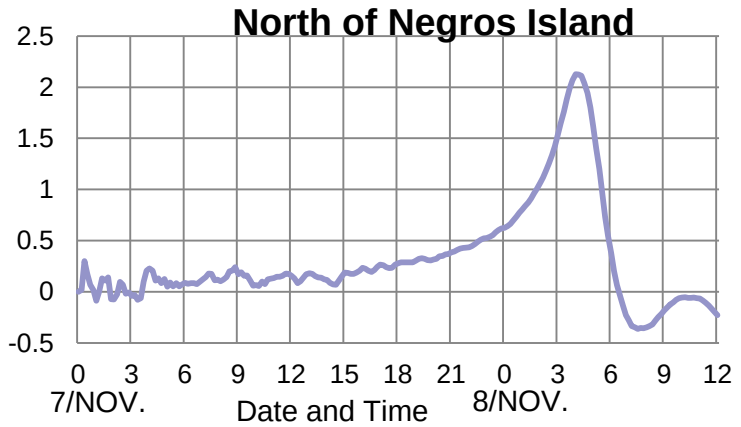


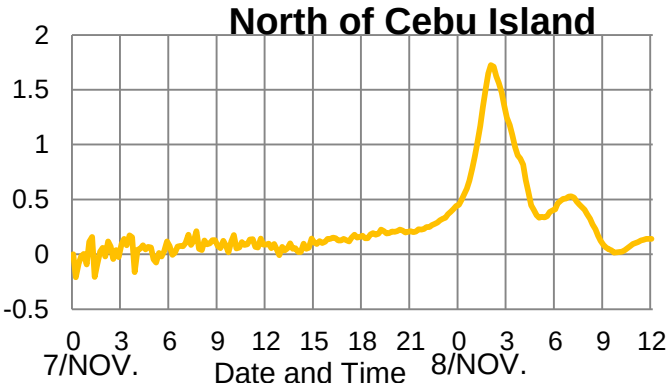


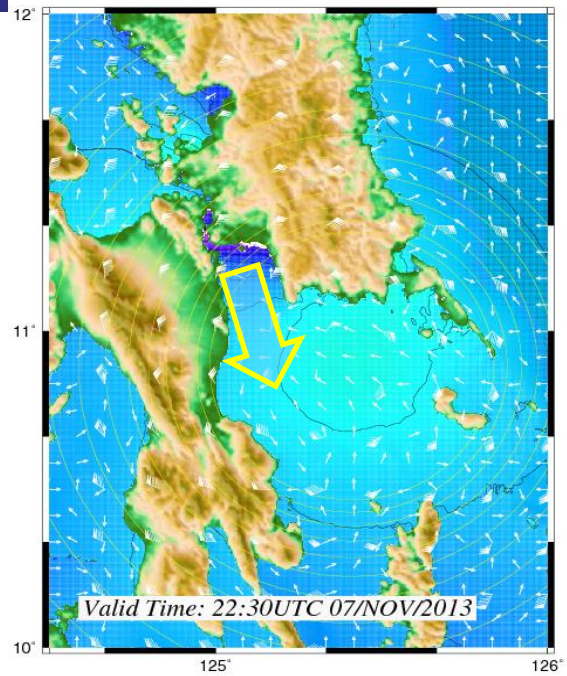




Storm surge (m)



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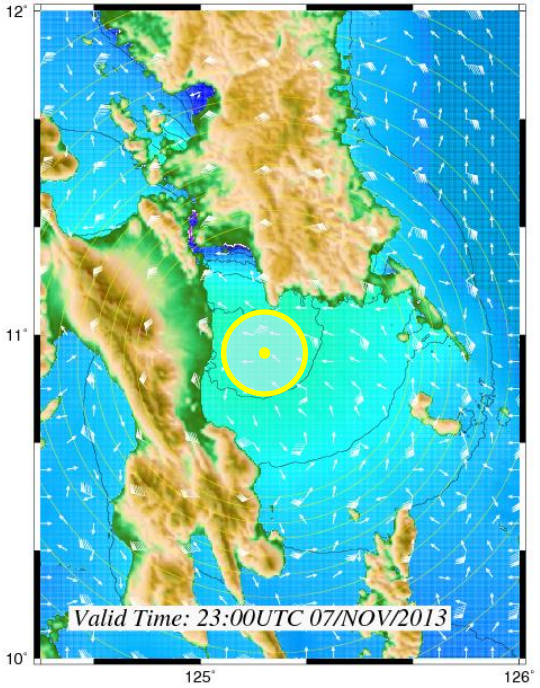
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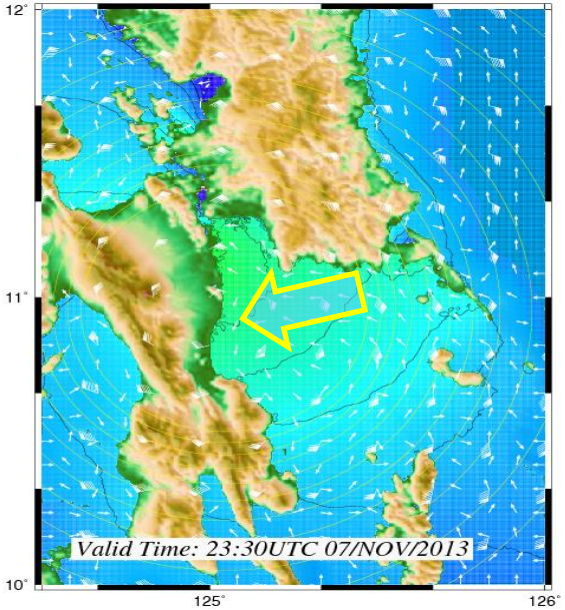
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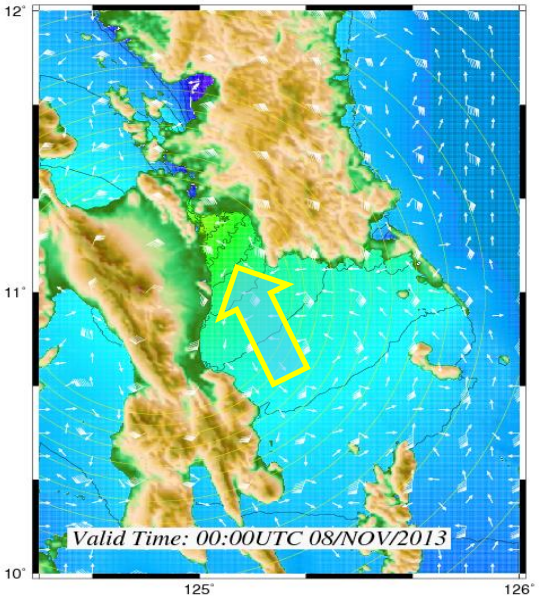
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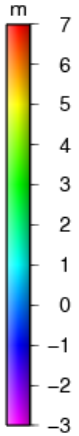
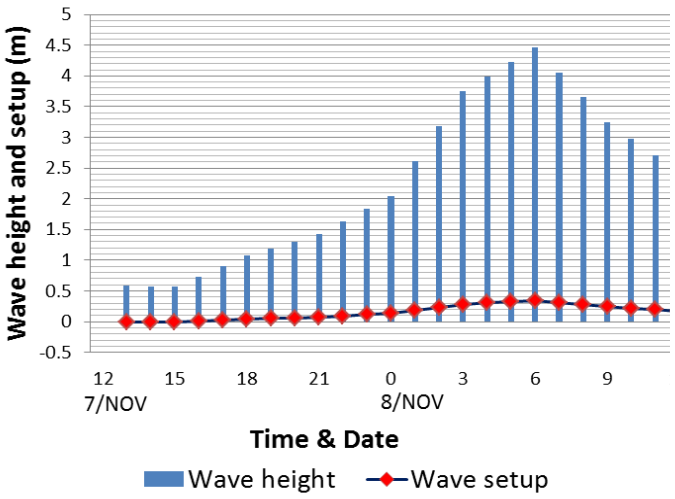
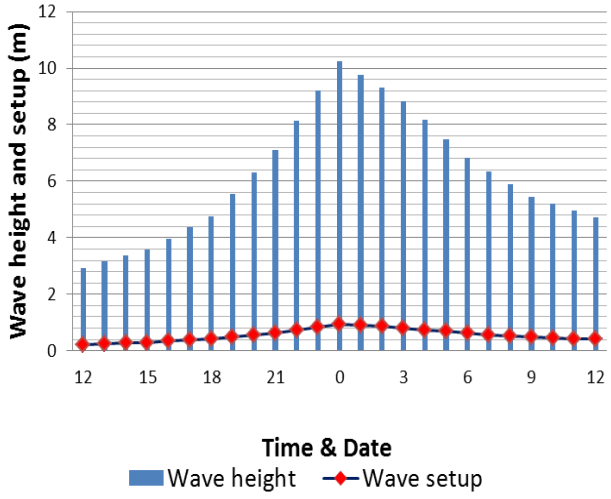
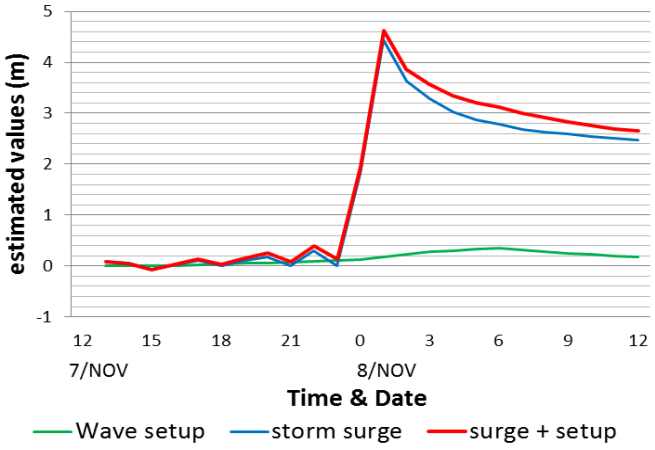
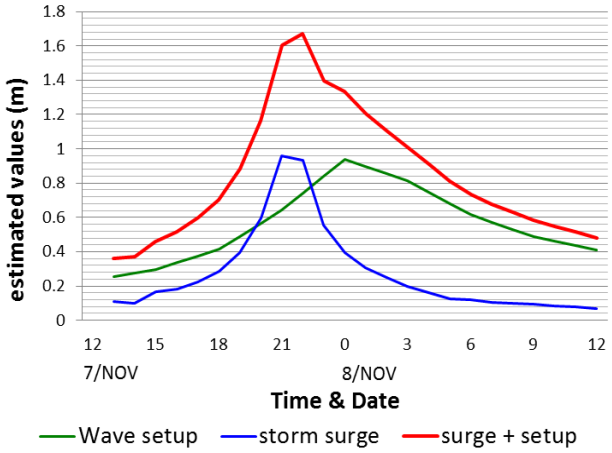

m
7
6
5
4
3
2
1
0
−1
−2
−3

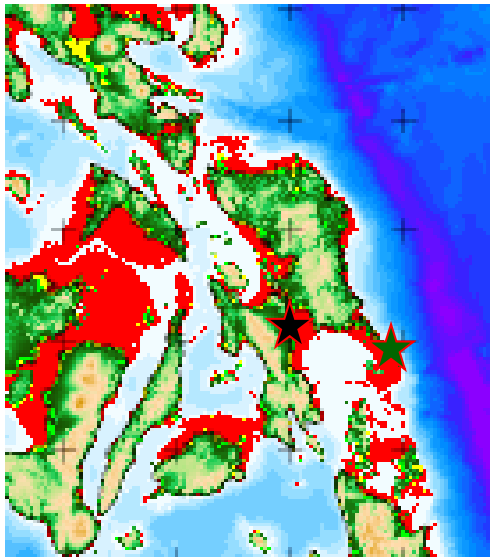
Storm surges at Tacloban and Guiuan











Tacloban

Guiuan

Simulated wave, wave setup, and storm surges at Tacloban and Guiuan. (Guiuan was much influenced by wave setup.)

Any Questions?

The JMA Mascot "*Harerun*"

(The word "hare" means fine weather in Japanese.)