Storm surge hindcasting using a fully coupled model of surge and wave
- Case study of Typhoon Haiyan surge

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Aim and Background

- Impact of
  - Wave dependent sea surface drag (Janssen, 1989 & 1991) with levelling off
  - Wave-current interaction induced bottom drag (Signell et al., 1990)
- on Haiyan surge 2013
- using a coupled model of surge and wave
  - 2 dimensional depth integrated storm surge model
  - wave model, SWAN

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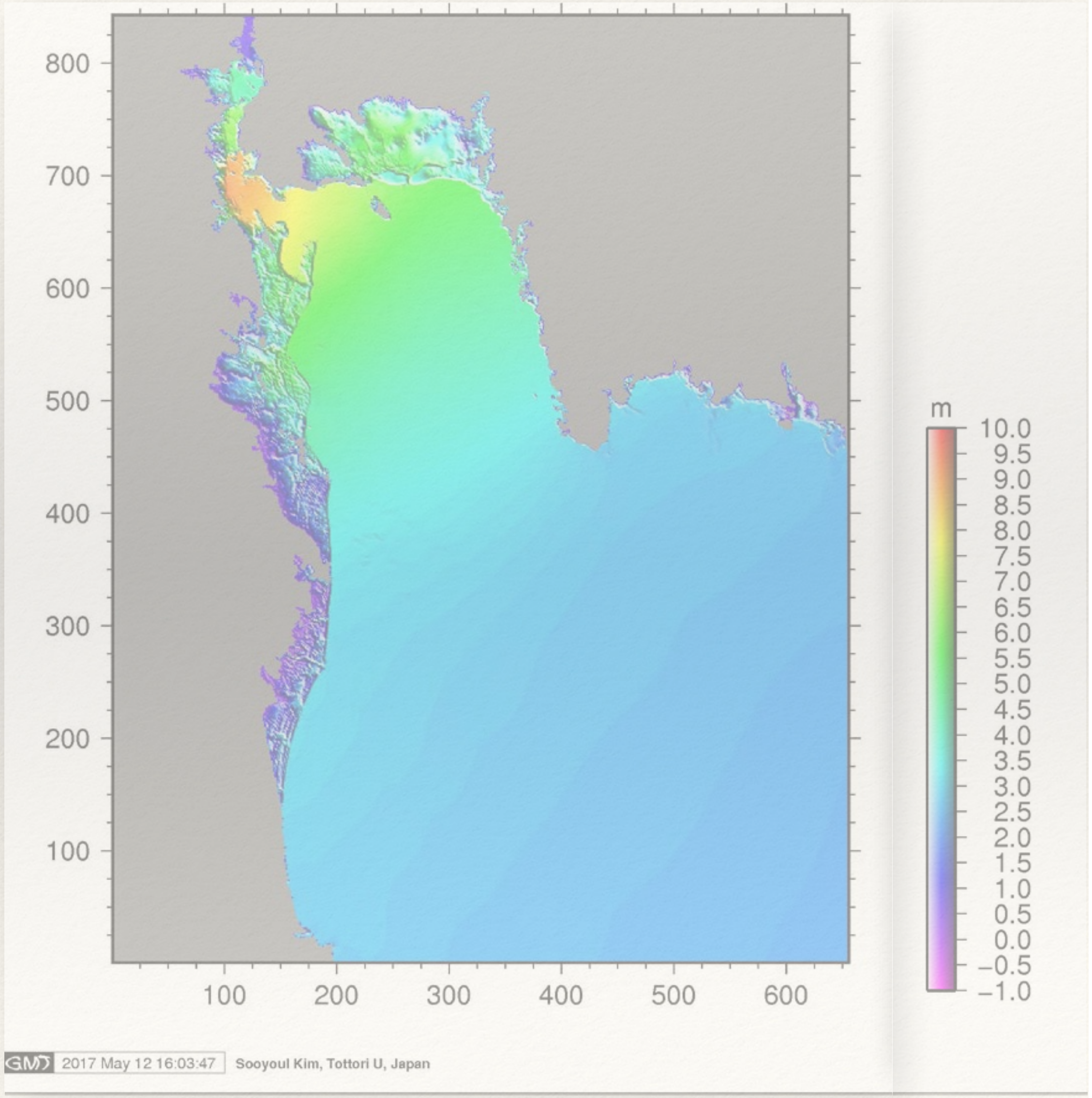
Content

- Wave dependant sea surface drag with levelling off
- Wave&current interaction-induced bottom drag
- Surge simulations by SuWAT
- Results
- Summary



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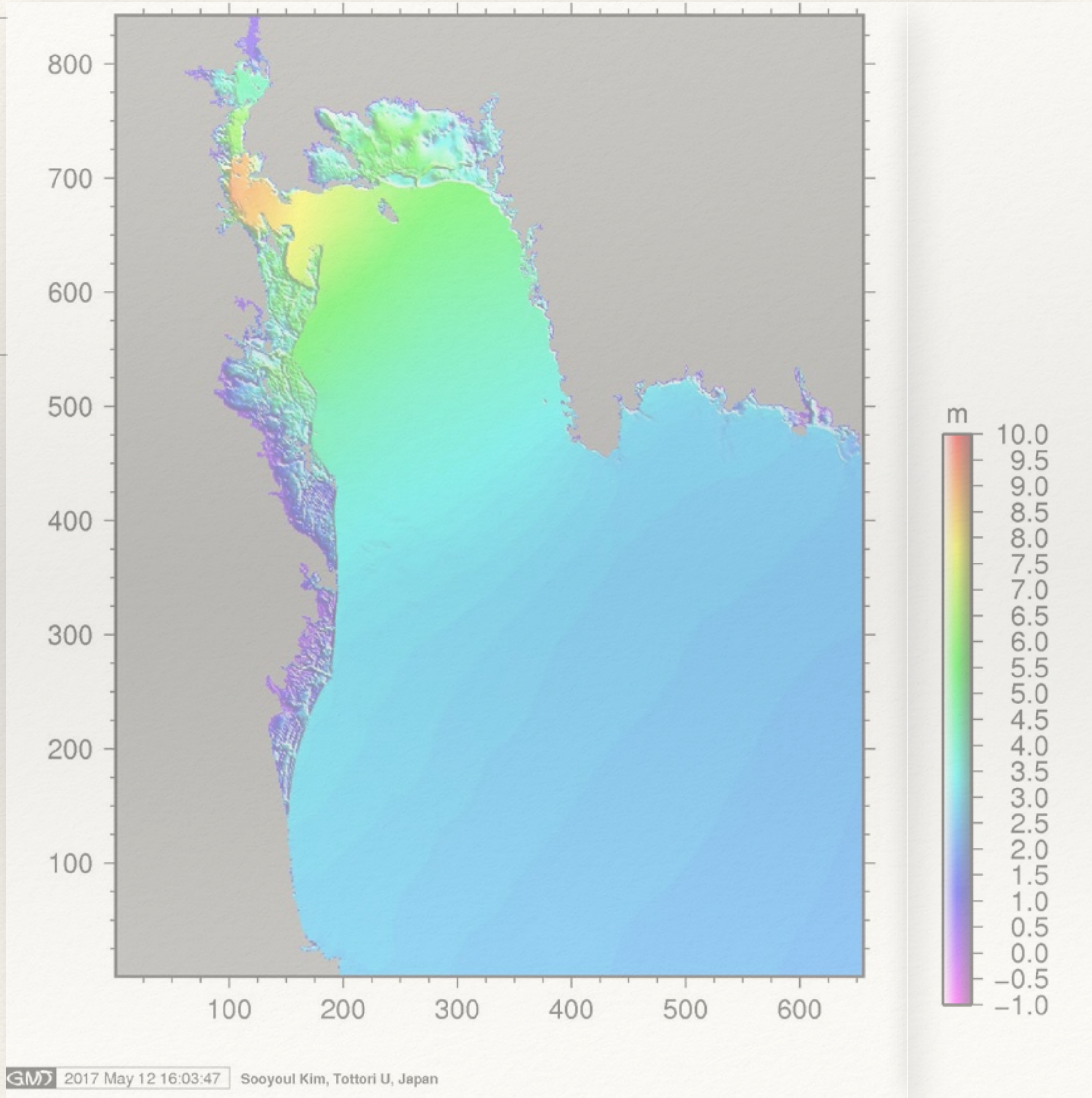
The drag coefficient, C_d, in sea surface layer



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The drag coefficient, C_d, in sea surface layer

- Wave growth term in SWAN

$$S_{in}(\sigma, \theta) = A + BE(\sigma, \theta)$$

  - A: the linear wave growth term
  - BE: the exponential wave growth term

The drag coefficient, C_d, in sea surface layer

- Wave growth term in SWAN

$$S_{in}(\sigma,\theta) = A + BE(\sigma,\theta)$$

  - A: the linear wave growth term
  - BE: the exponential wave growth term
- Cd in the linear wave growth term
  - Transfer U10 to U* the friction velocity ($u_*^2 = C_D U_{10}^2$)

Wu (1982):

$$C_D = \begin{cases} 1.2875 \times 10^{-3} & \text{for } U_{10} < 7.5\text{m/s} \\ (0.8 + 0.065 U_{10}) \times 10^{-3} & \text{for } U_{10} > 7.5\text{m/s} \end{cases}$$

Zijlema et al (2012):

$$C_D = (0.55 + 2.97\tilde{U} - 1.49\tilde{U}^2) \times 10^{-3}$$

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The drag coefficient, C_d, in sea surface layer

- Wave growth term in SWAN

$$S_{in}(\sigma,\theta) = A + BE(\sigma,\theta)$$

  - BE: the exponential wave growth term

- Janssen's wave dependent Cd in the exponential wave growth term (1991) and following Mastenbroek et al.(1993) accounting for sea state
  - Wind profile: $U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z+z_e+z_0}{z_e}\right)$ Turbulent stress $\tau_t = \rho_a(\kappa z)^2\left(\frac{\partial U}{\partial z}\right)^2$
  - Effective roughness: $z_e = \frac{z_0}{\sqrt{1-\tau_w/\tau}}$
  - Wind speed-capped Wave dependent Cd

$$C_D = u_*^2/U(z)^2 = \left[\kappa/\ln\left(\frac{z+z_e-z_0}{z_e}\right)\right]^2 \rightarrow \tau_s = \rho_a C_D \vec{U}_{10}|\vec{U}_{10}|$$

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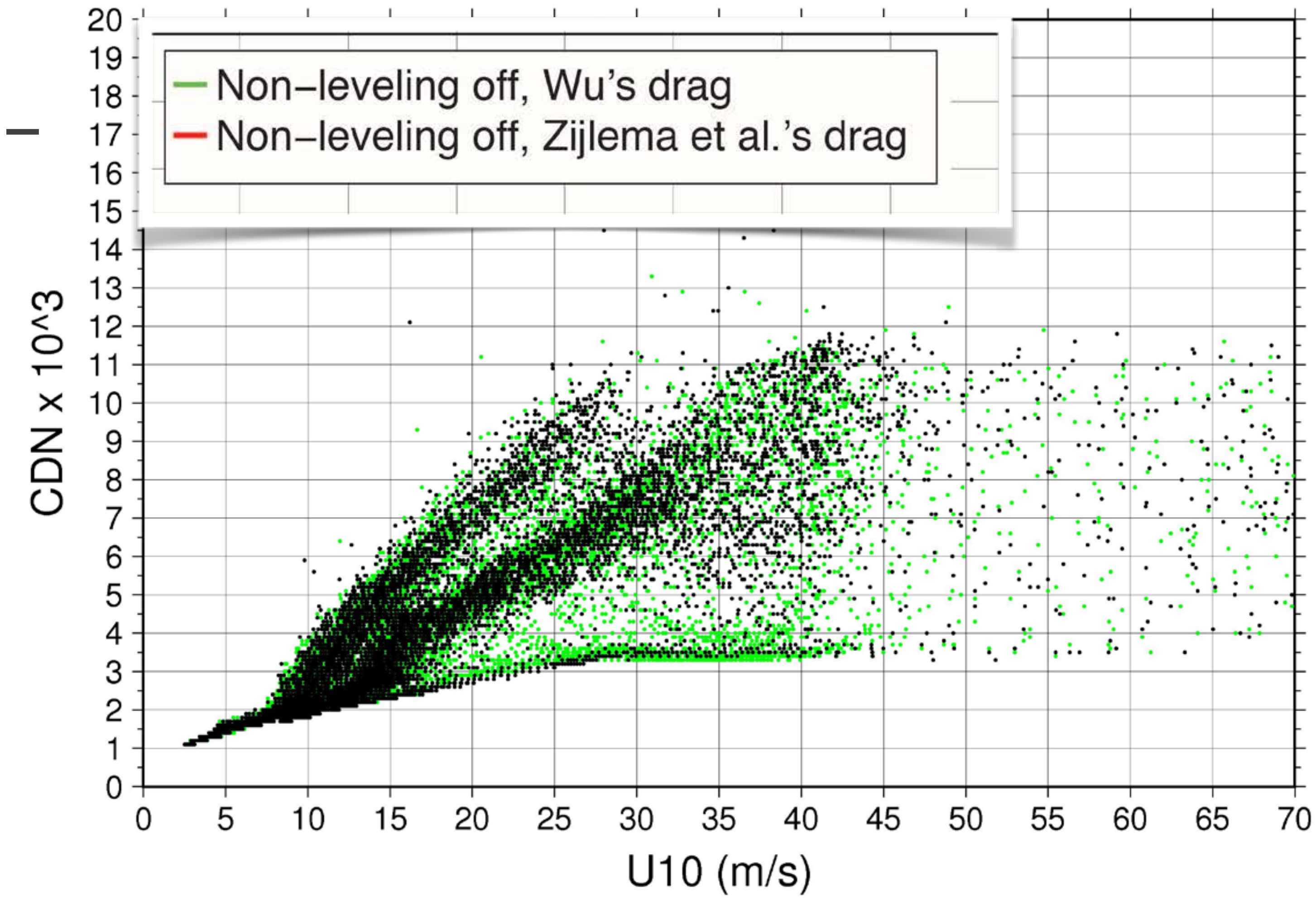
Estimated wave dependent C_d without levelling off



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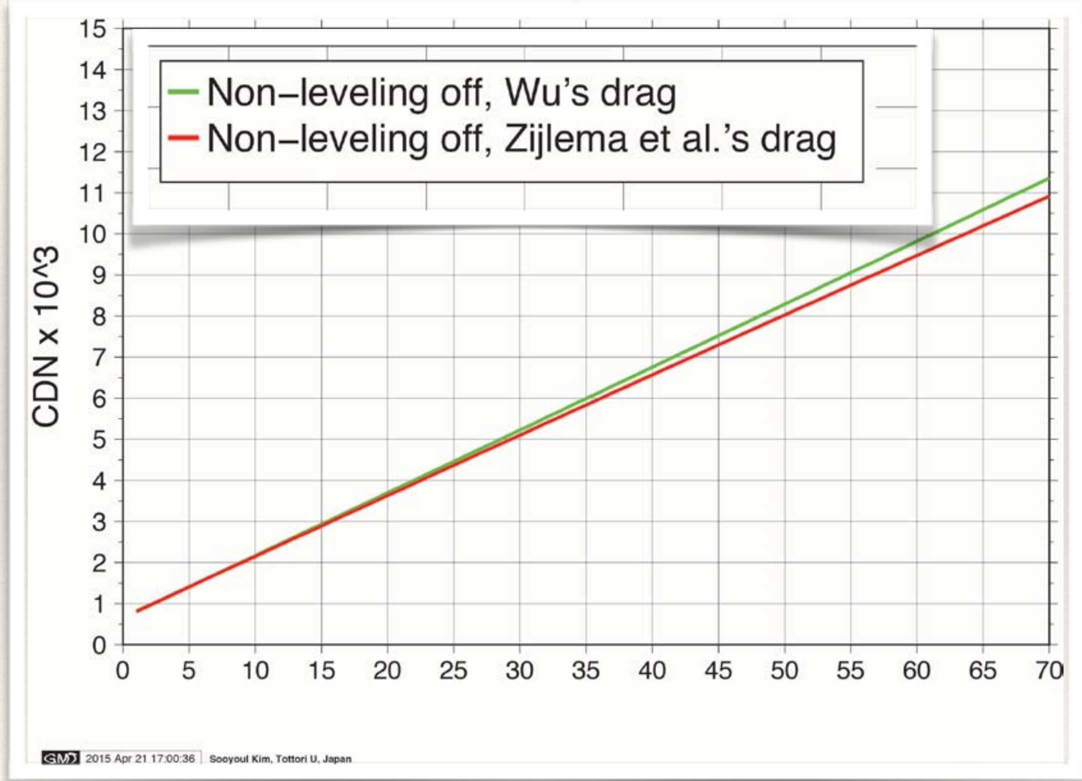
The best-fitted wave dependent C_d to the 2nd-order polynomial

Moon et al. 2008
and others

- Threshold for a levelling off based on measurements
  - 33 *m/s* : Powell et al. (2003)
  - 30-40 *m/s* : Donelan et al. (2004)
  - 22-23 *m/s* : Black et al. (2007)



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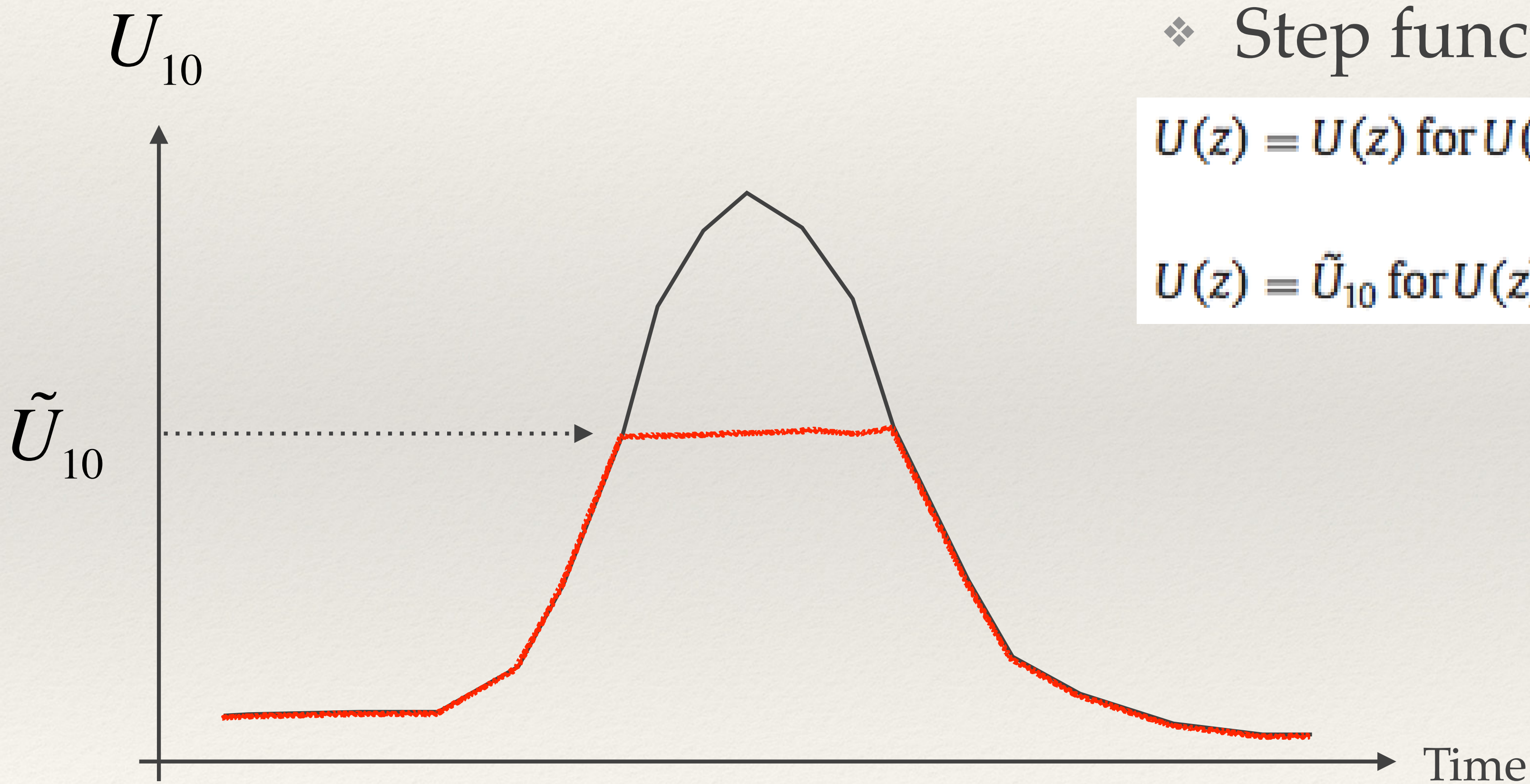
Levelling Wave dependent Cd off in the exponential term

- Wind profiles only in the exponential term



- Step functions

$$U(z) = U(z) \text{ for } U(z) < \tilde{U}_{10}$$

$$U(z) = \tilde{U}_{10} \text{ for } U(z) \geq \tilde{U}_{10}$$

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Levelling off in the exponential term

- Levelling off the wave dependent Cd in the exponential wave growth term
  - Step functions

$$U(z) = U(z)\ \text{for}\ U(z) < \tilde{U}_{10}$$

$$U(z) = \tilde{U}_{10}\ \text{for}\ U(z) \geq \tilde{U}_{10}$$

  - Wind profile

$$U(z) = \frac{u_*}{k} \ln\left(\frac{z + z_e + z_0}{z_e}\right), \text{ if } U(z) < \tilde{U}(z)$$

$$\tilde{U}(z) = \frac{u_*}{k} \ln\left(\frac{z + z_e + z_0}{z_e}\right), \text{ if } U(z) \geq \tilde{U}(z)$$

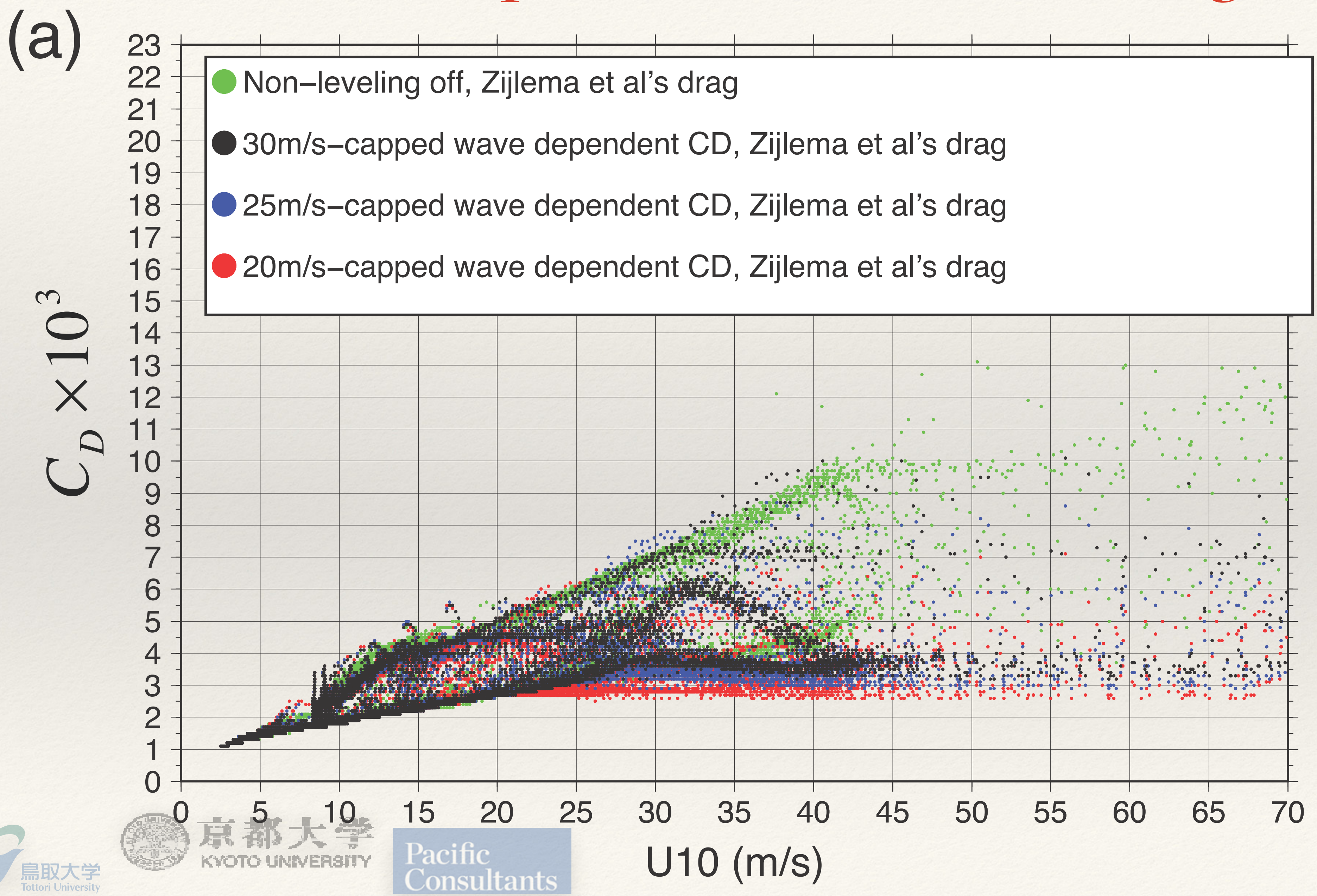
  - Wind speed-capped Wave dependent Cd

$$C_d = u_*^2 / U(z)^2 = \kappa / \ln\left(\frac{z + z_e + z_0}{z_e}\right), \text{ if } U(z) < \tilde{U}(z)$$

$$C_d = u_*^2 / \tilde{U}(z)^2 = \kappa / \ln\left(\frac{z + z_e + z_0}{z_e}\right), \text{ if } U(z) \geq \tilde{U}(z)$$

(Kim et al. 2015, Ocean Modelling)

Scattered wave dependent C_d with levelling off



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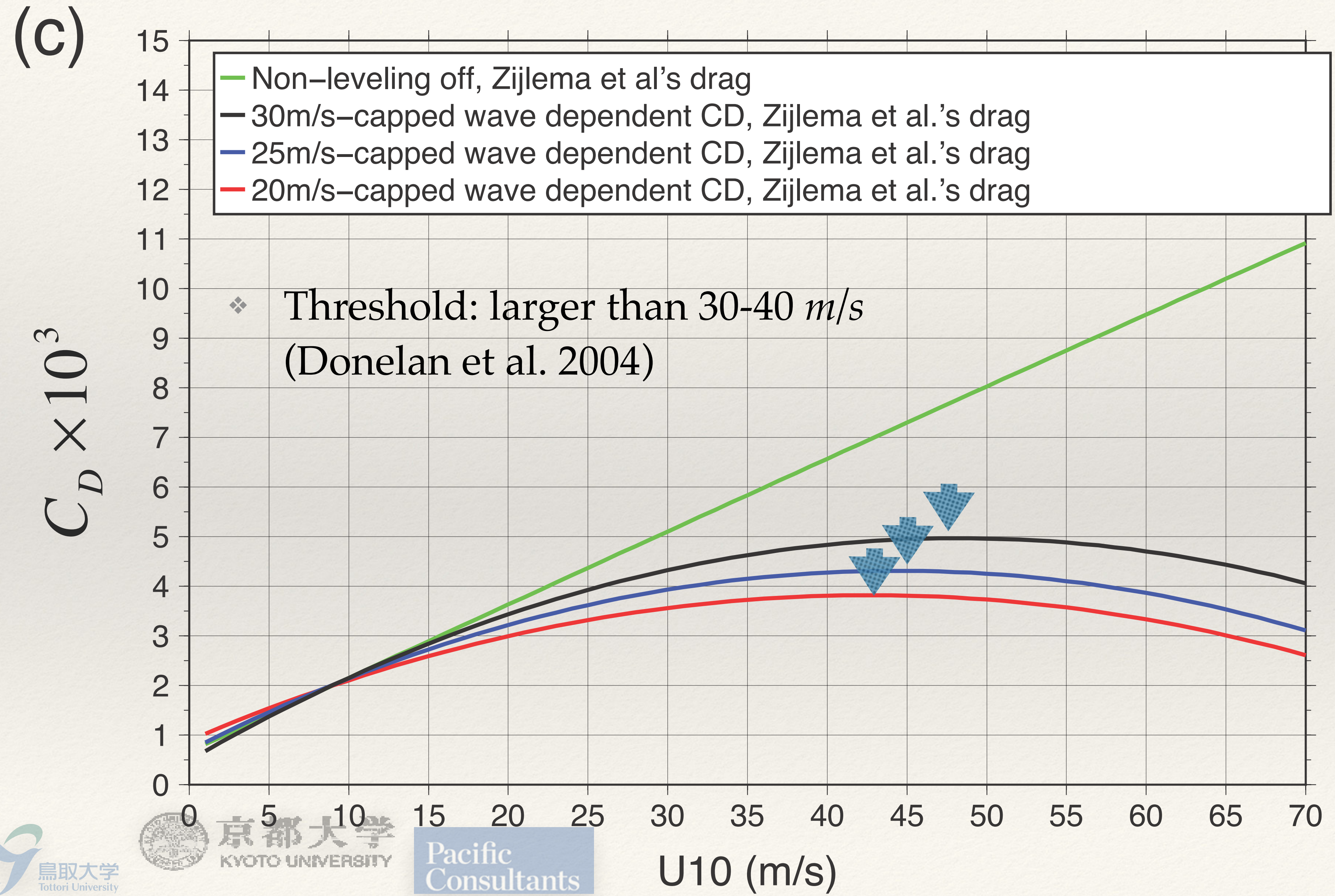
The best-fitted wave dependent *Cd* to the 2nd-order polynomial



- Threshold: larger than 30-40 *m/s* (Donelan et al. 2004)

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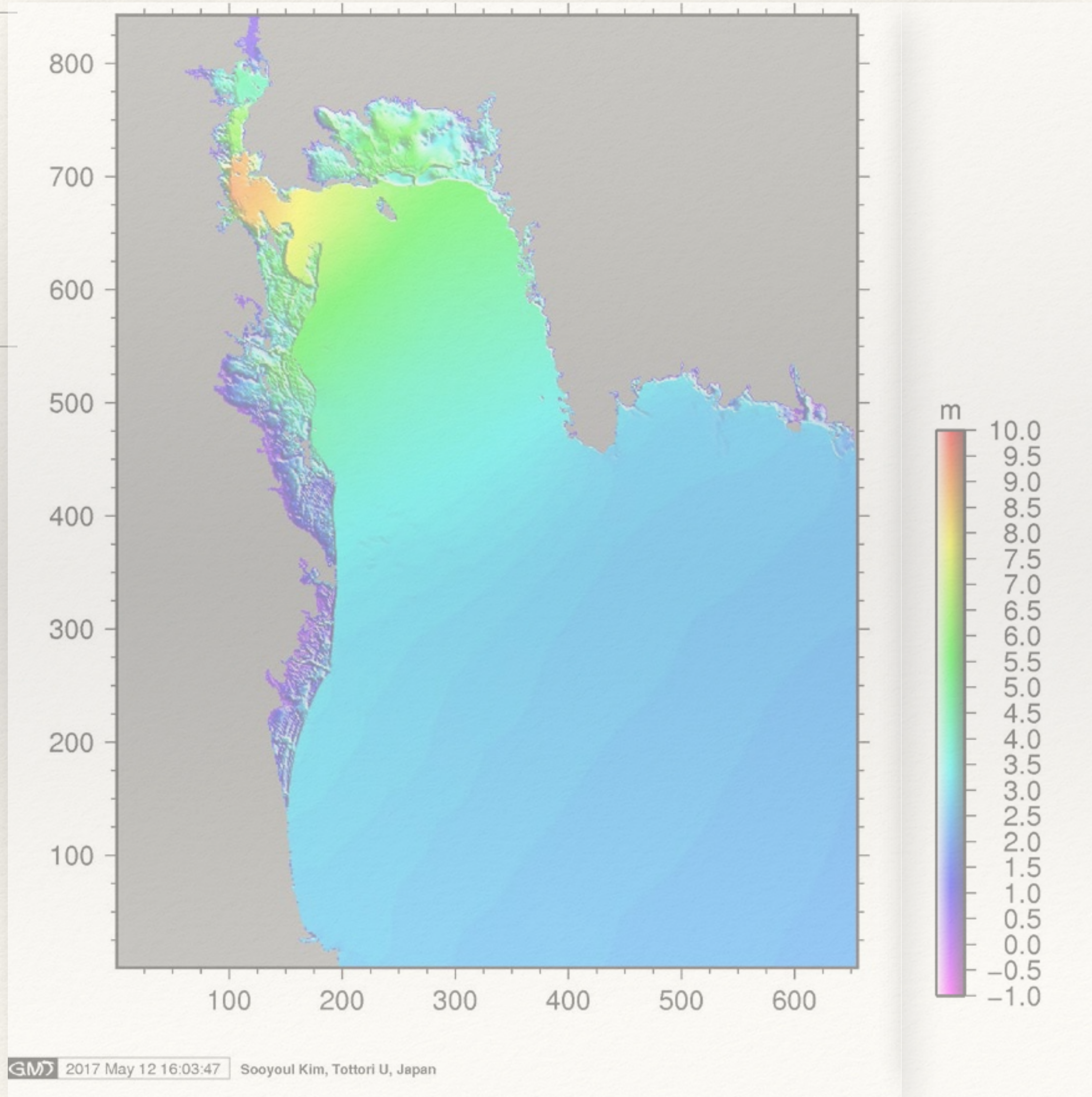
The wave&current interaction-induced bottom drag, f_c



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The wave&current interaction-induced bottom drag, f_c

- Conventional method
  - Manning number, n,

$$\tau_b = \rho_w g n^2 \frac{\vec{Q}\left|\vec{Q}\right|}{h^{7/3}} \longrightarrow \tau_b = \rho_w \frac{f_c}{8} \frac{\vec{Q}\left|\vec{Q}\right|}{h^2}$$

$$f_c = 8 \times \frac{g n^2}{h^{1/3}}$$

Signell et al., 1990 & Davies and Lawrence, 1995

$$k_{bc} = k_b \left[C_1 \frac{U_{*cw} A_b}{U_w k_b} \right]^{\beta} \qquad f_c = 2\left[\frac{K}{\ln\left(30 z_r / k_{bc}\right)} \right]^2$$

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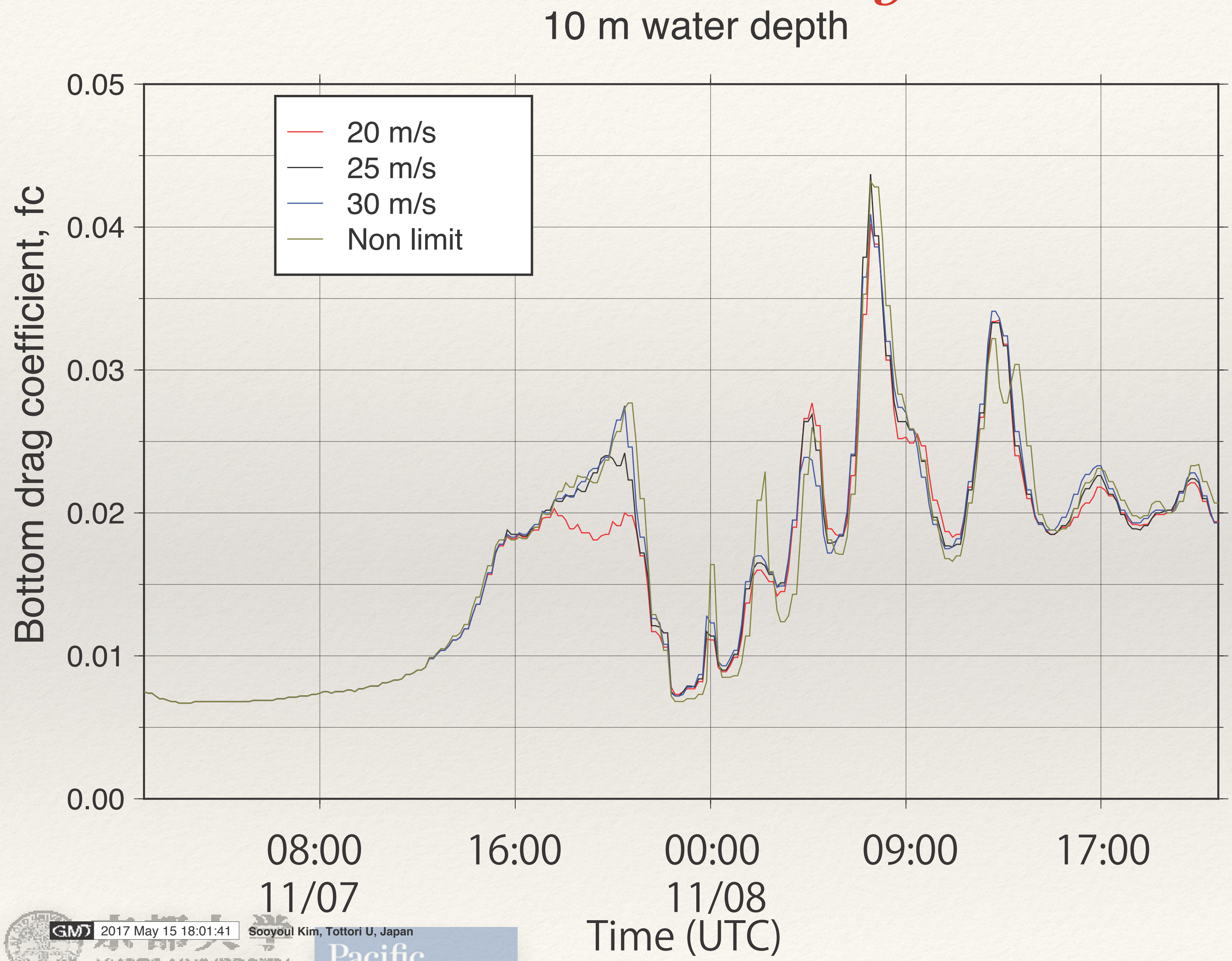
Time series of f_c



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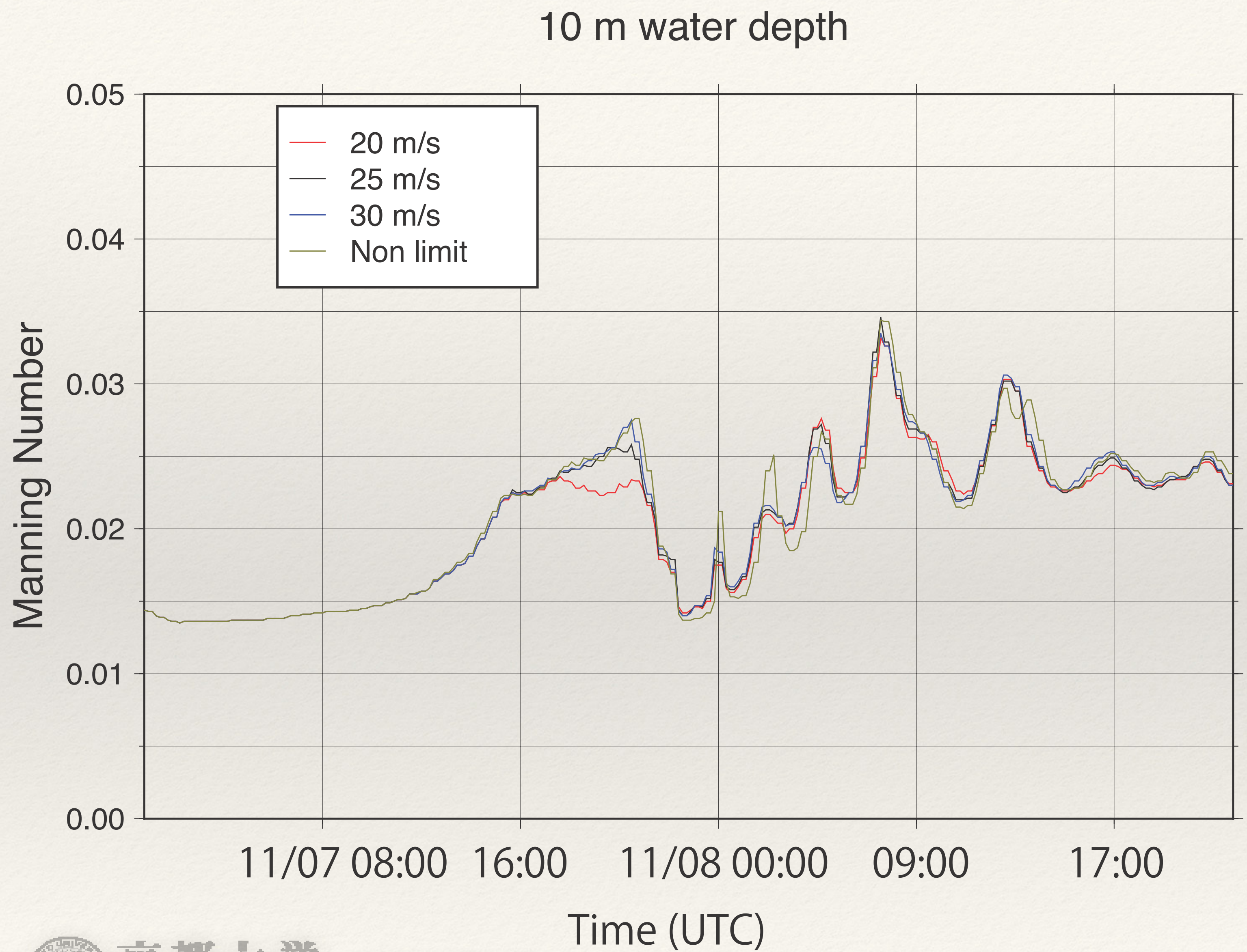
Time series of Manning Number converted from f_c



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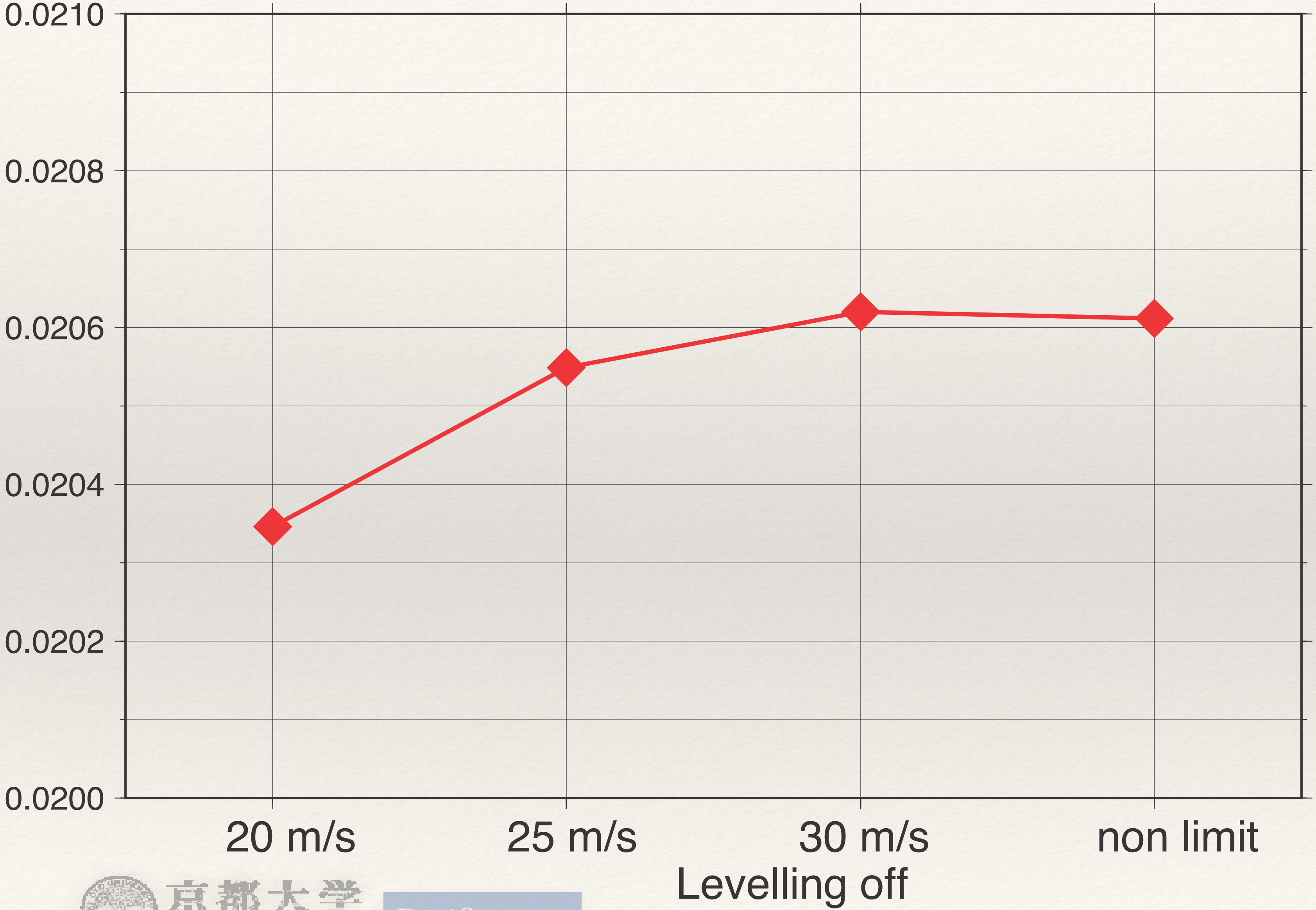
Averaged Manning Number converted from f_c



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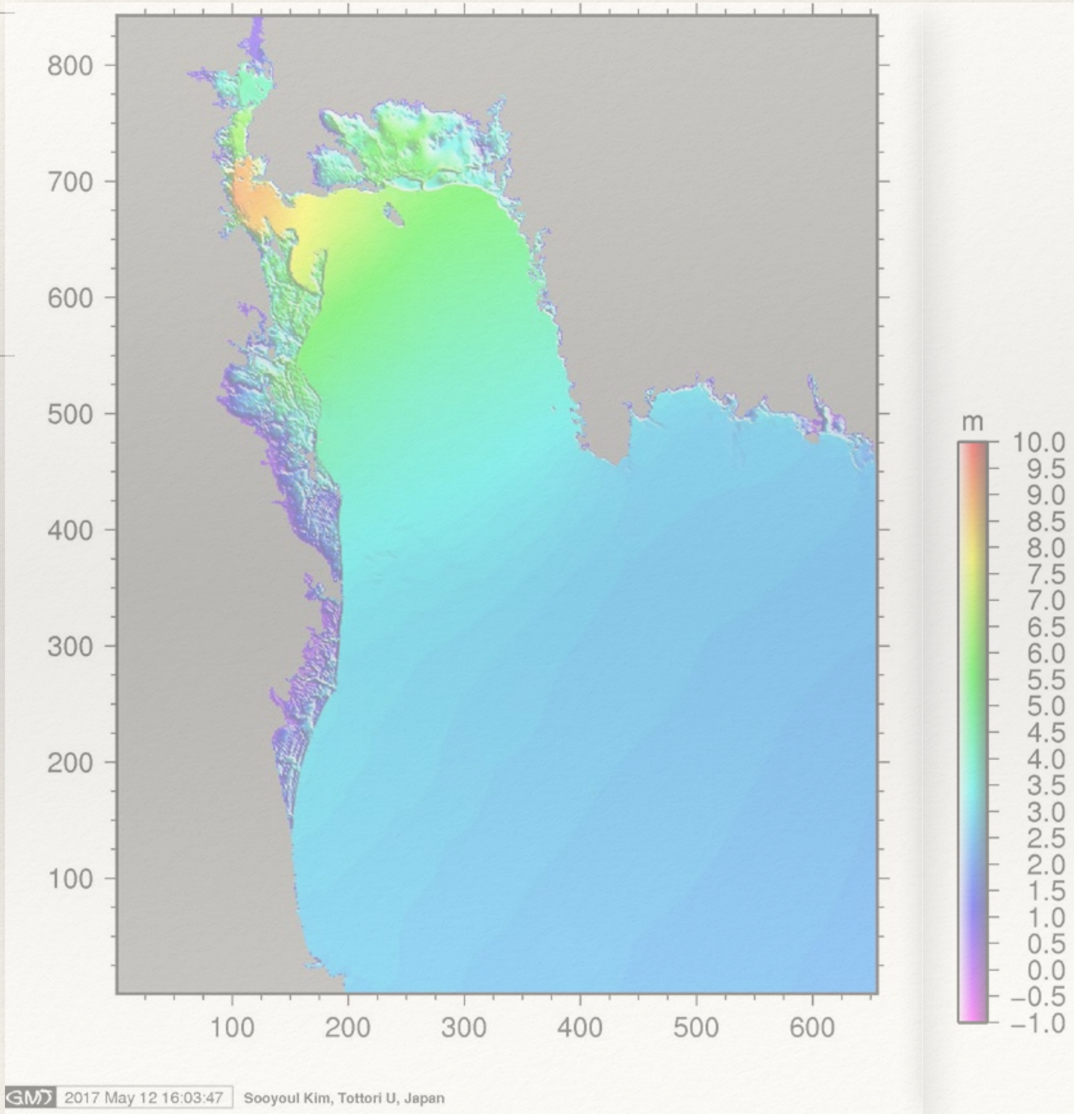
Haiyan storm surge simulations

using

1. wind speed capped-wave dependent Cd

2. wave current interaction-induced bottom drag



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A coupled model of Surge, Wave and Tide (SuWAT)

- A coupled model of Surge, WAve and Tide (SuWAT, Kim et al. 2008, 2010)
  - Storm surge: 2DDI model (0.2 sec)
  - Wave: SWAN (900 sec)
  - Information exchange (900 sec) of Cd, fc, current and water level
  - FDM, structured grid (2.43 km, 810 m, 270 m and 90 m)
  - Nesting scheme (four domains)
  - Message Passing interface (MPI) between two domains
- Parametric wind and pressure model
  - Schloemer's formula (1954)
  - Fujii and Mitsuta's formula (1986)
- Tide model (ignored)

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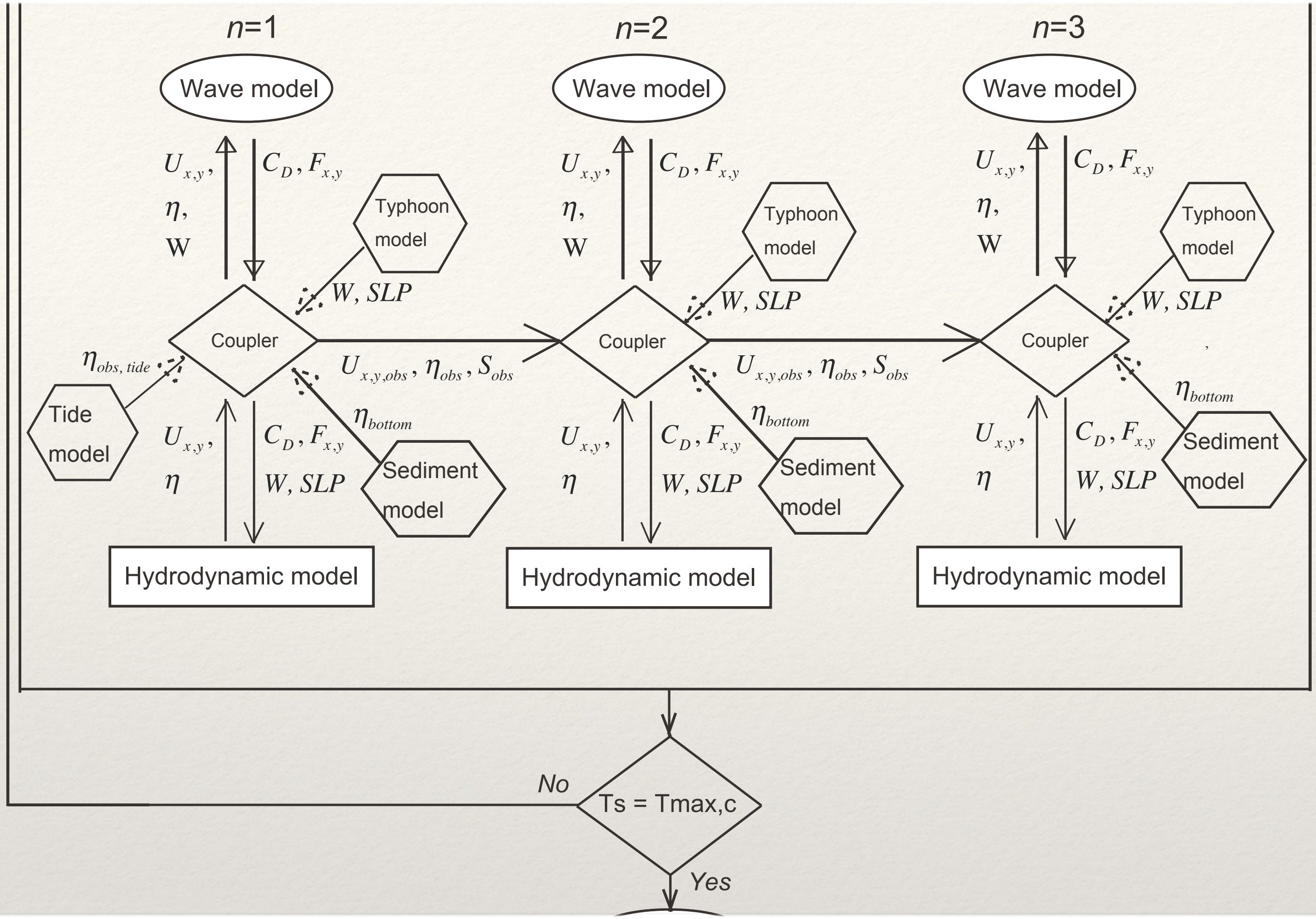


n : the domain level

Ts : the time step in the computation

Tmax,c : the end of time step for coupling runs

$U_{x,y}$: the current

η : the sea surface level

C_D : the wave dependent drag

$F_{x,y}$: the depth averaged-wave radiation stress

W : the wind

SLP : the sea level pressure

$U_{x,y,obs}$: the current for boundaries

η_{obs} : the sea surface level for boundaries

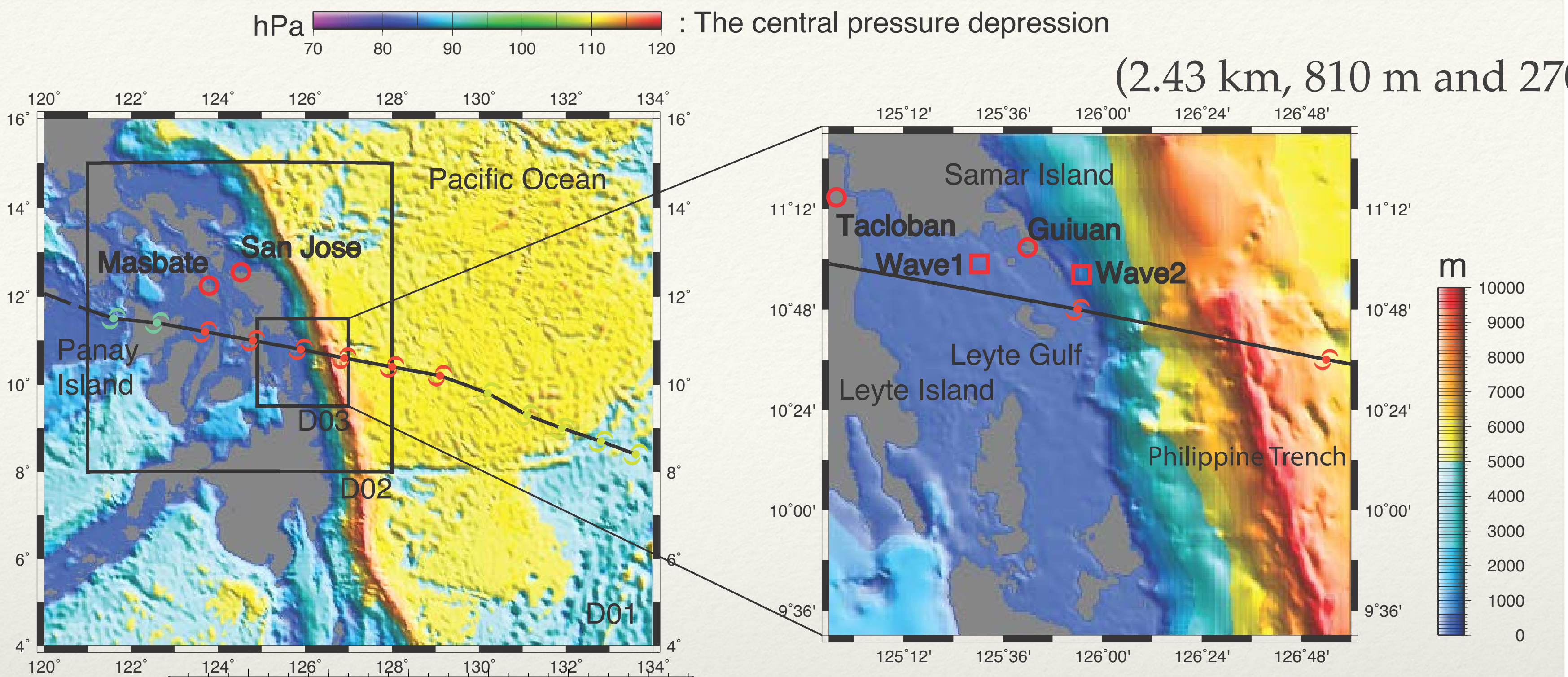
S_{obs} : the wave spectrum for boundaries

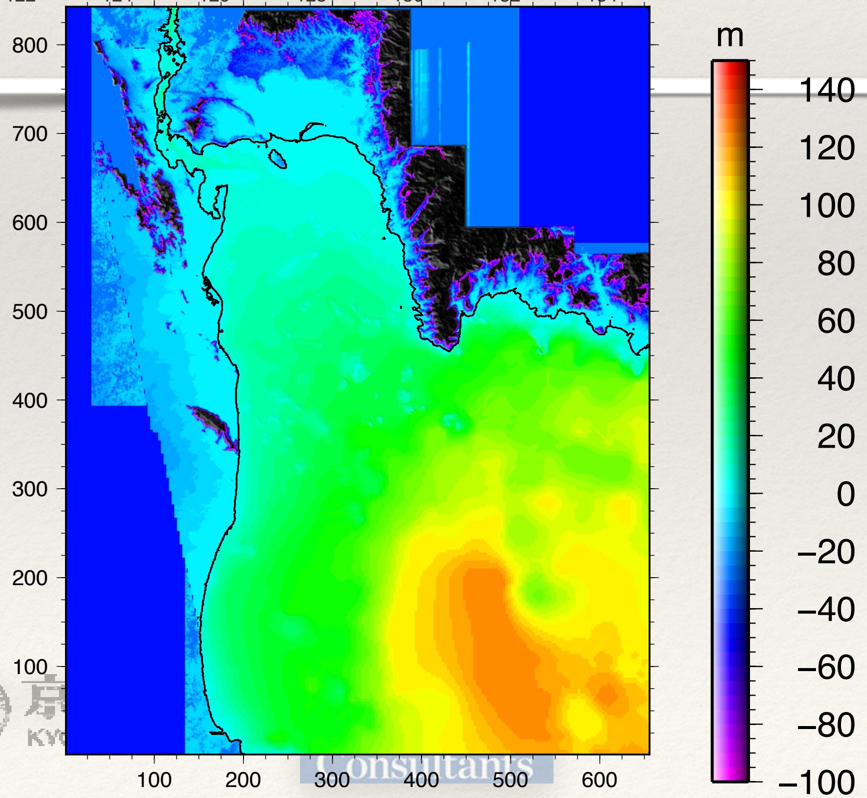
$\eta_{obs,\ tide}$: the tide obtained from global and/or regional barotropic inverse tidal solutions of the Oregon State University Tidal Inversion Software (OTIS)

η_{bottom} : the bed level

Coupling process

(2.43 km, 810 m and 270 m)



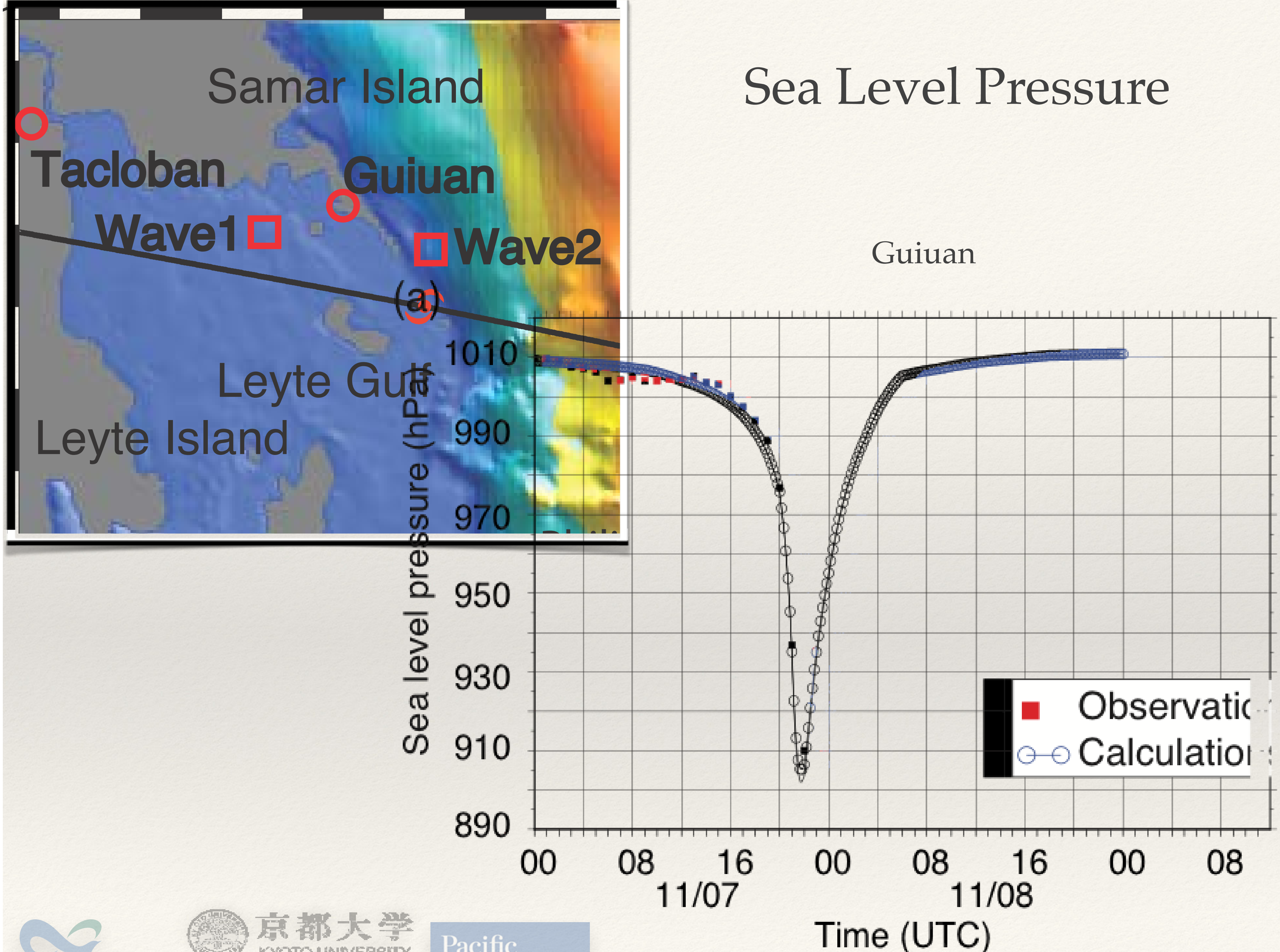


Flooding:

90 m: grid size

Manning Number: 0.04 in land

Sea Level Pressure



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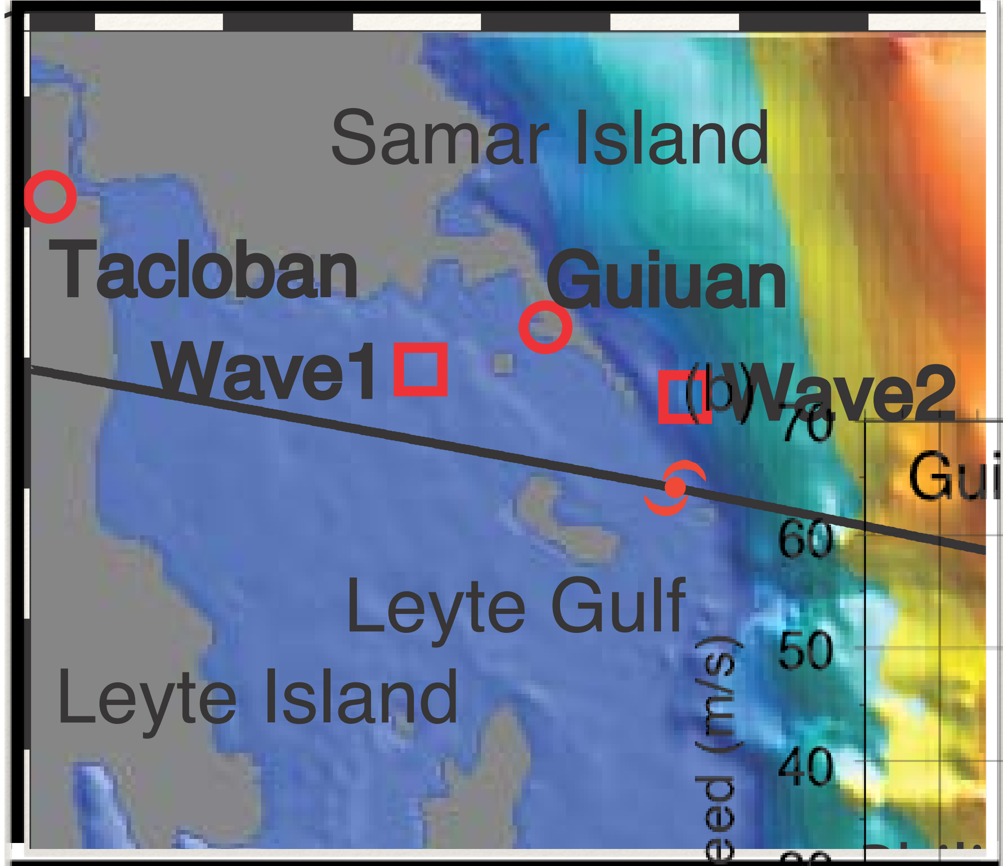
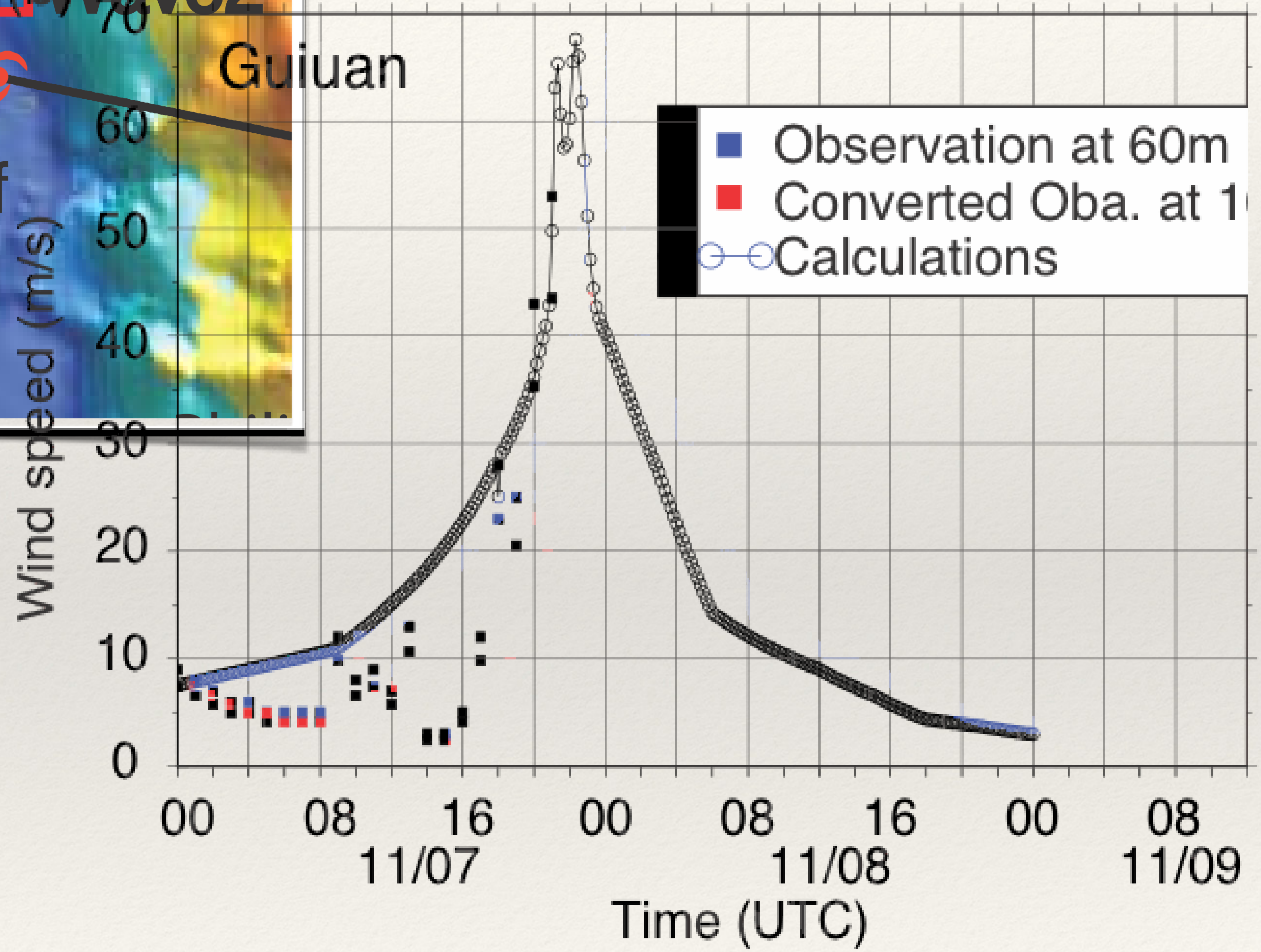
Wind speed, U10





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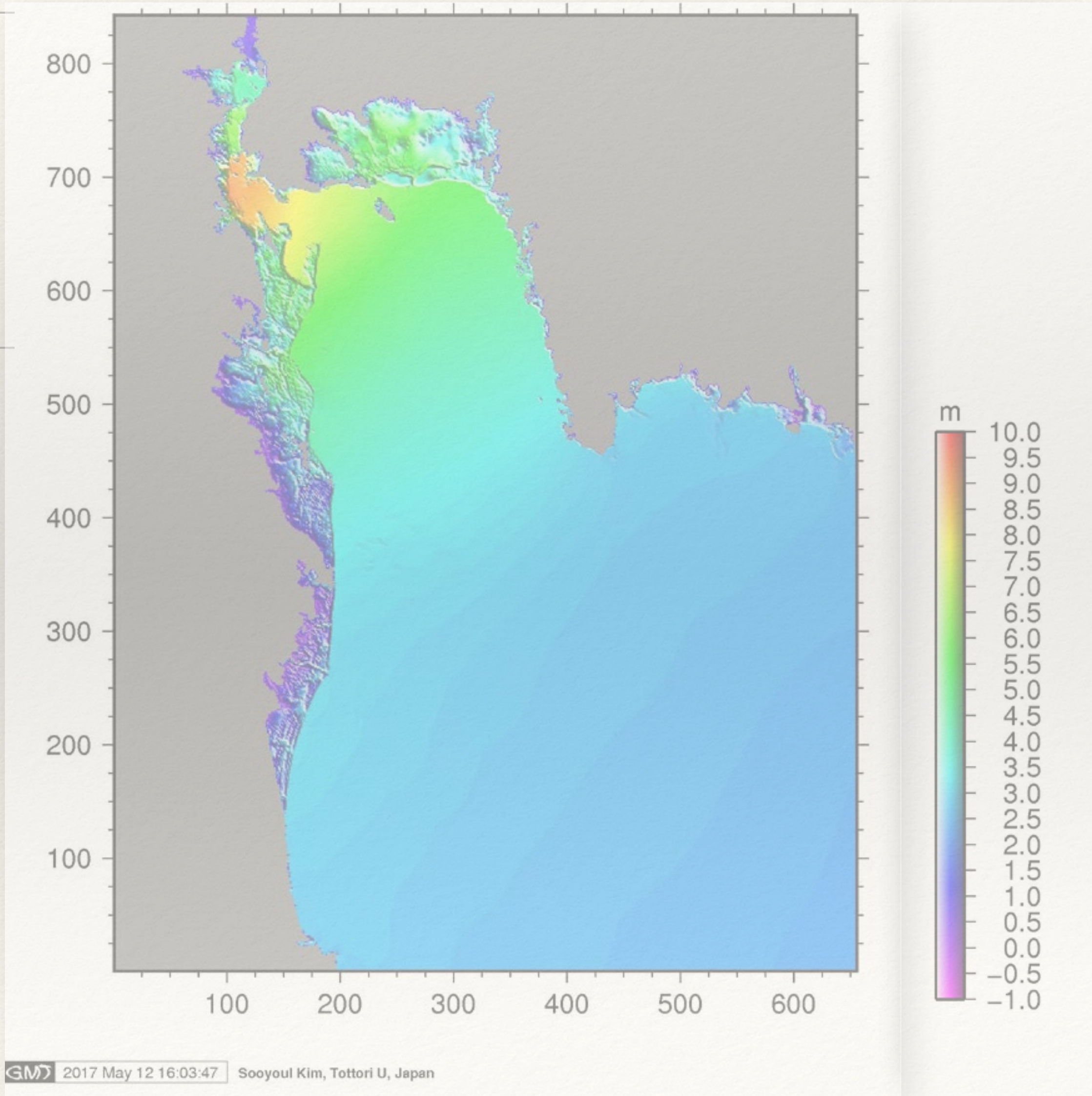
Haiyan storm surges



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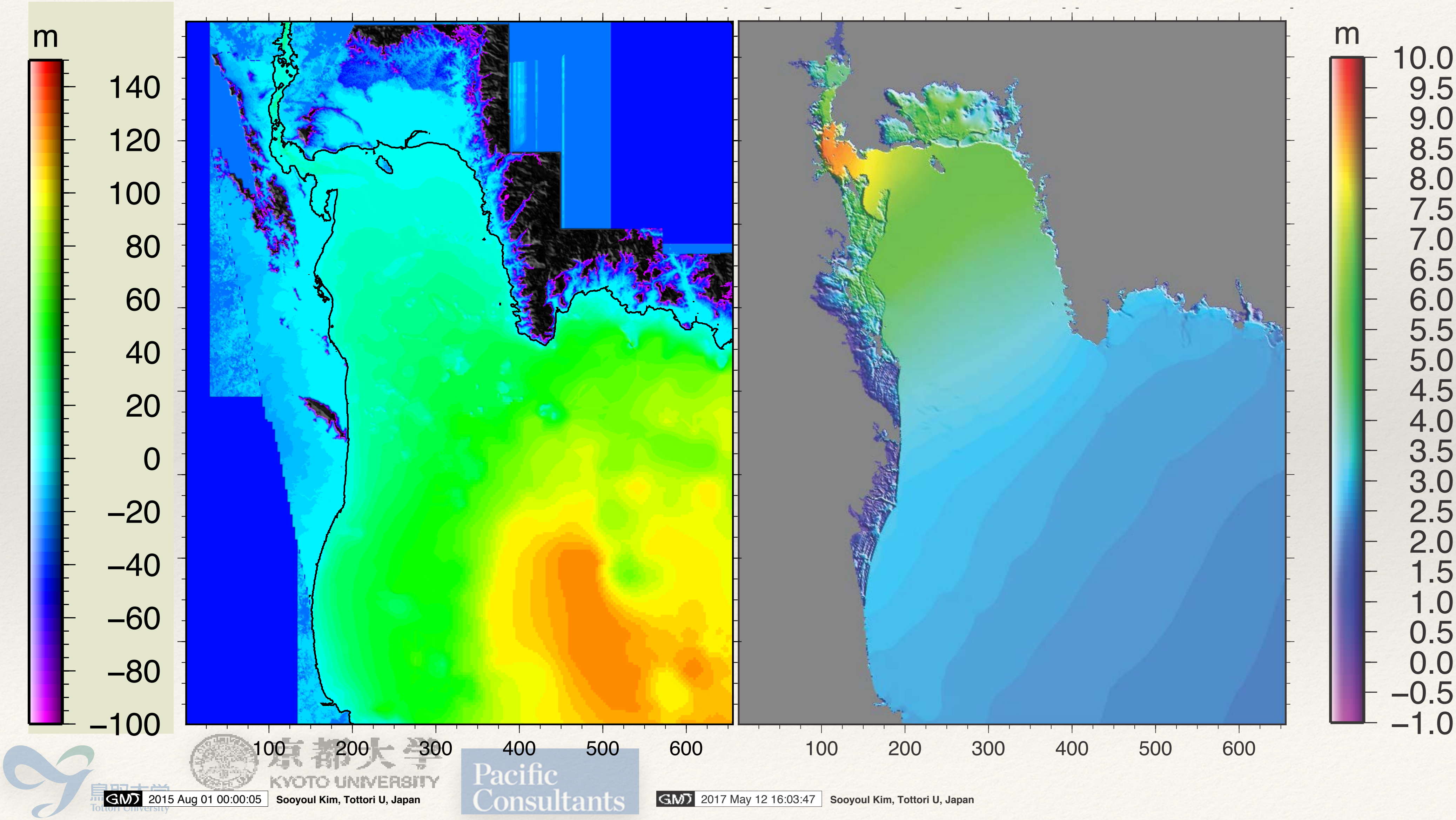
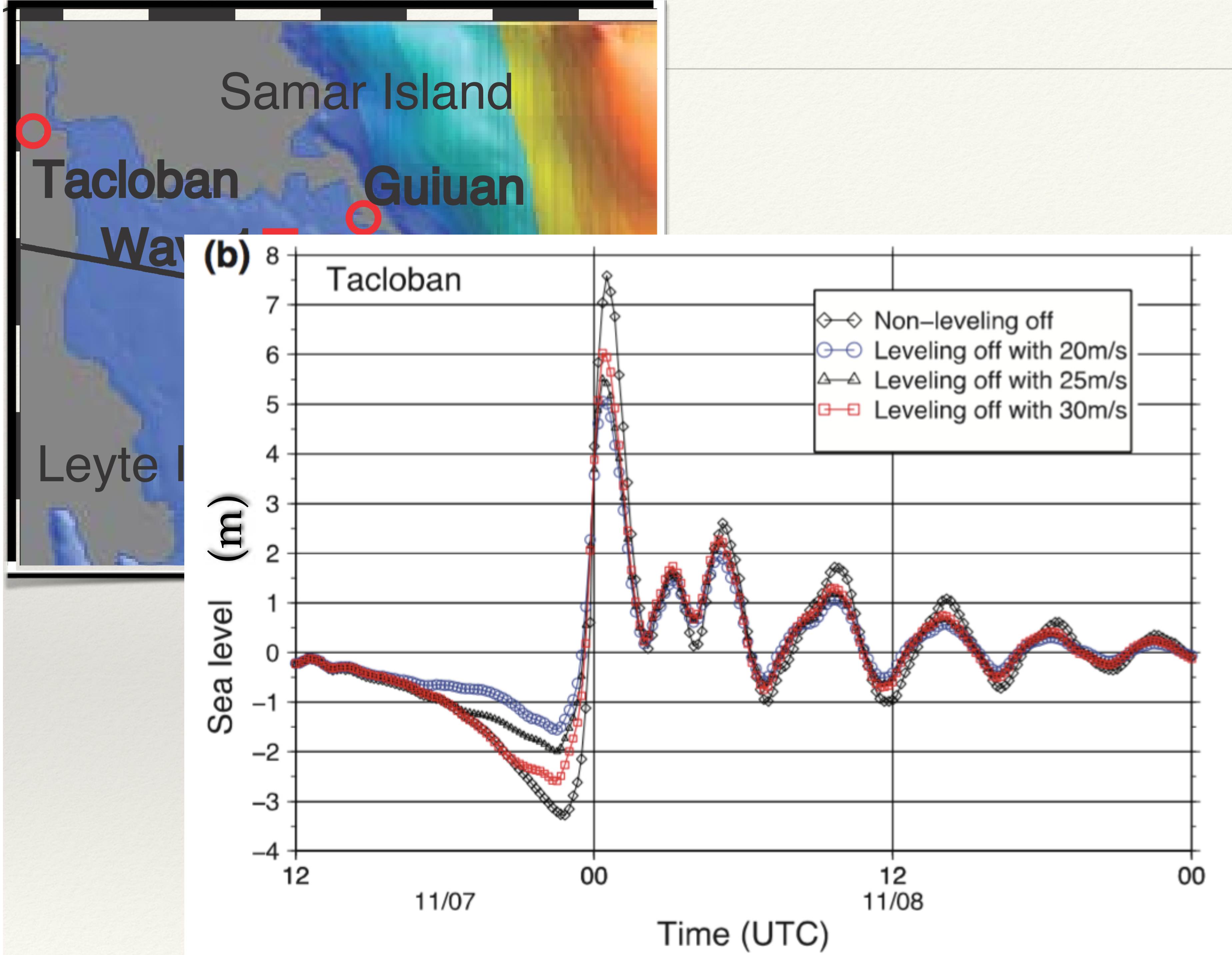
Highest surge levels with 25 m/s levelling off





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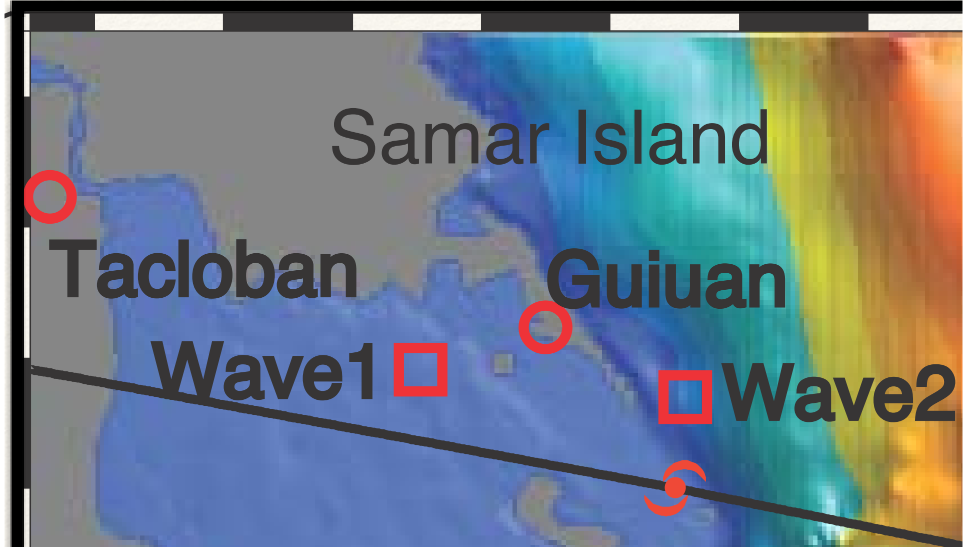
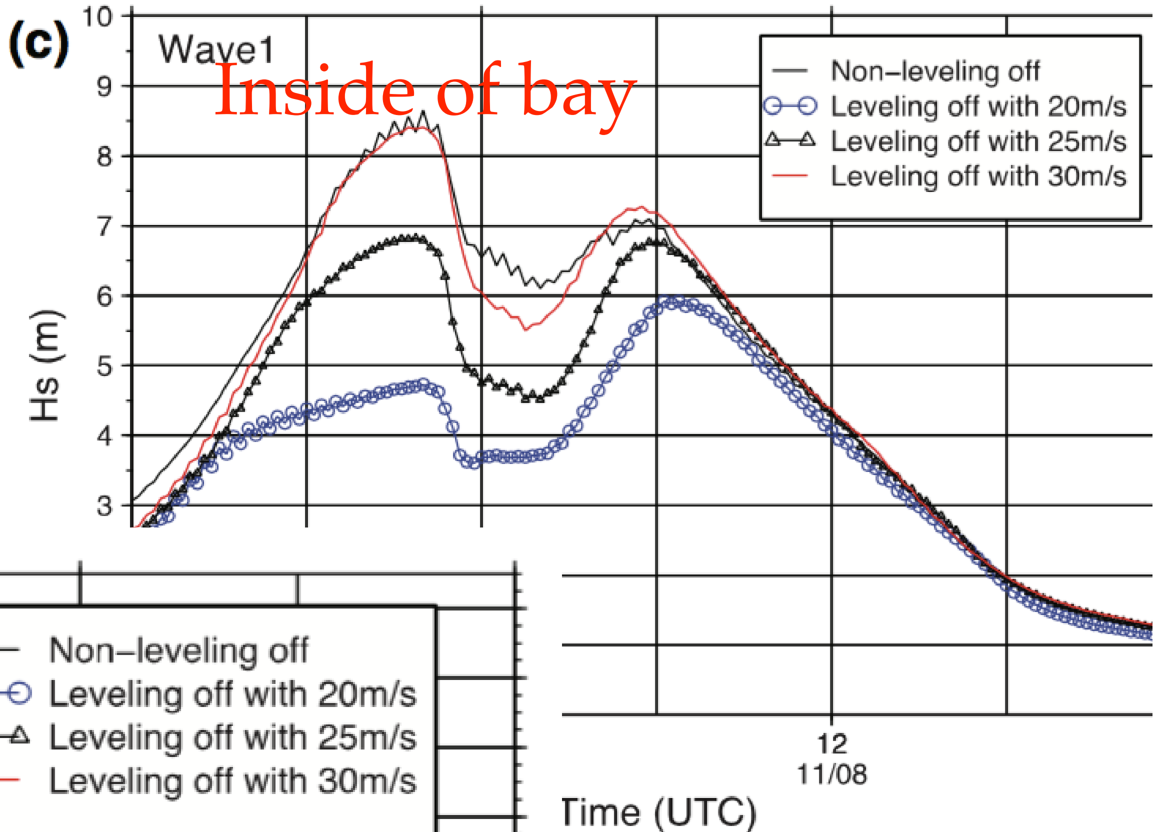
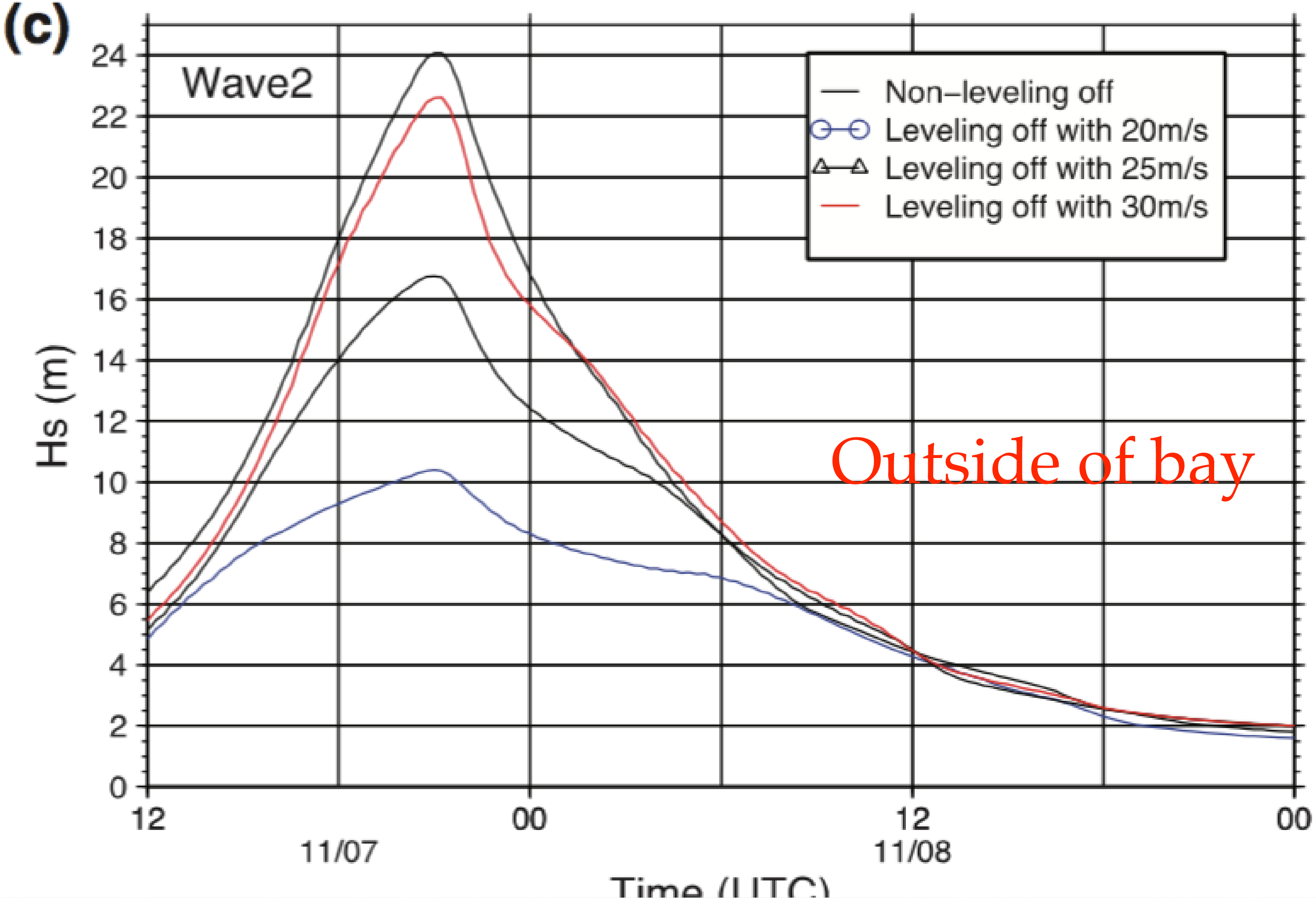


Samar Island
Tacloban
Guiuan
Wave1
Wave2

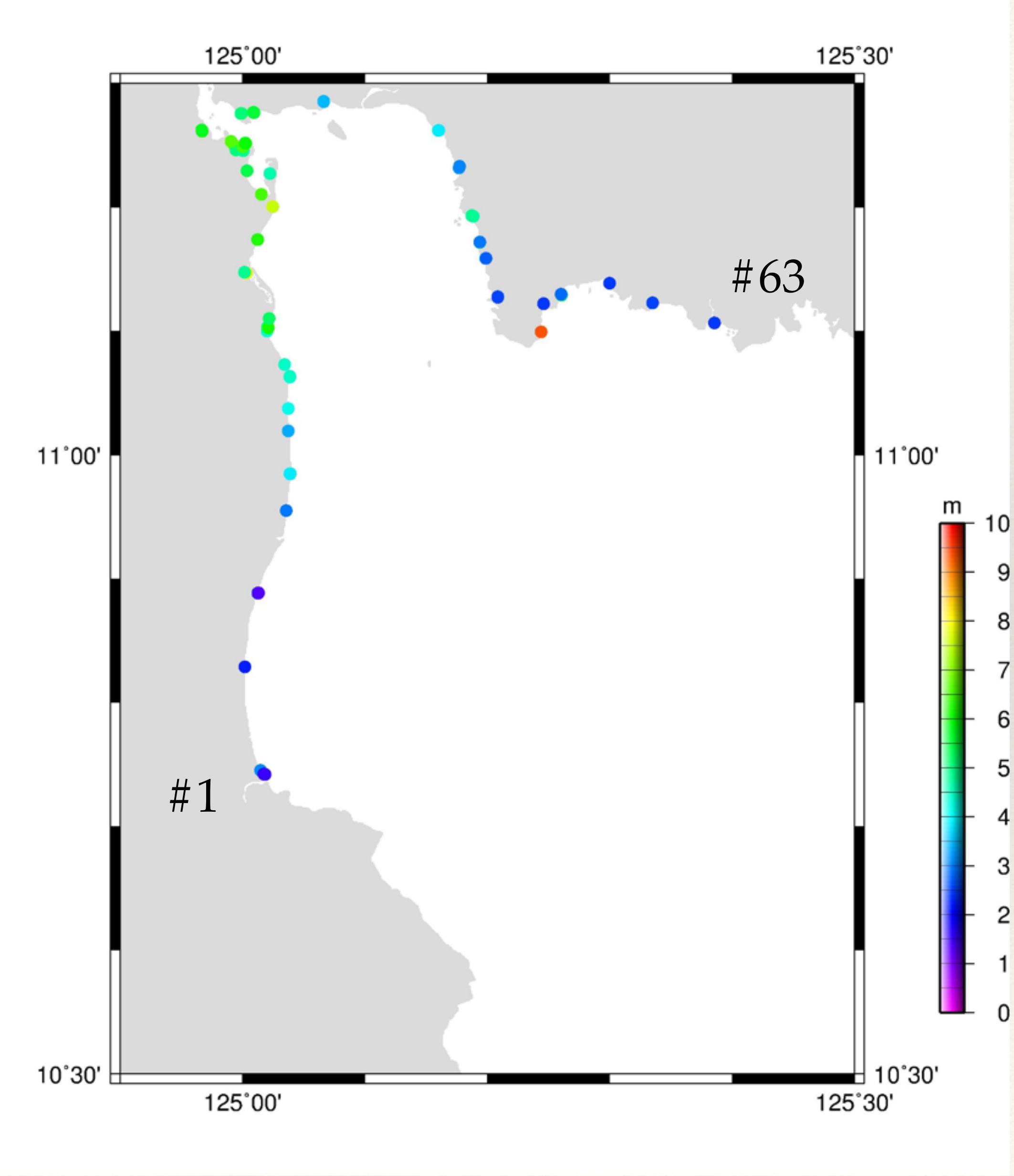


(c)
Wave1
Inside of bay
Non–leveling off
Leveling off with 20m/s
Leveling off with 25m/s
Leveling off with 30m/s
Hs (m)
10
9
8
7
6
5
4
3
12
11/08
Time (UTC)

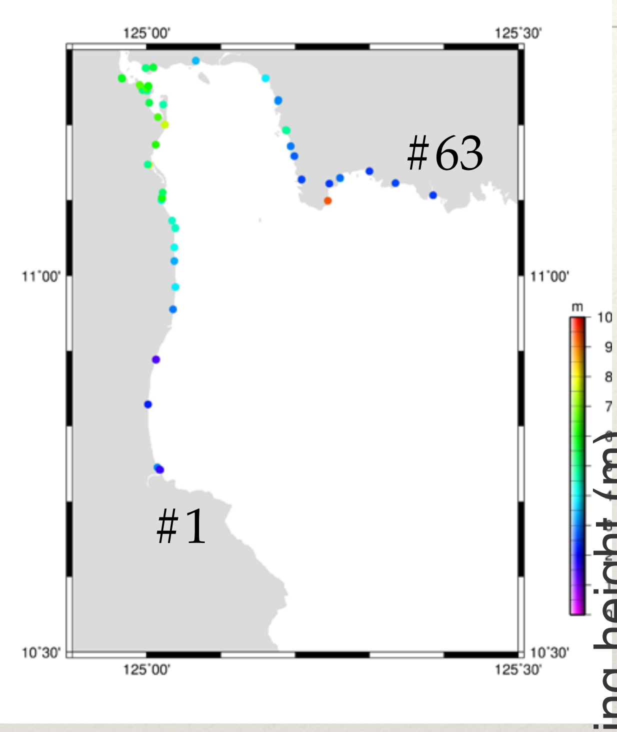


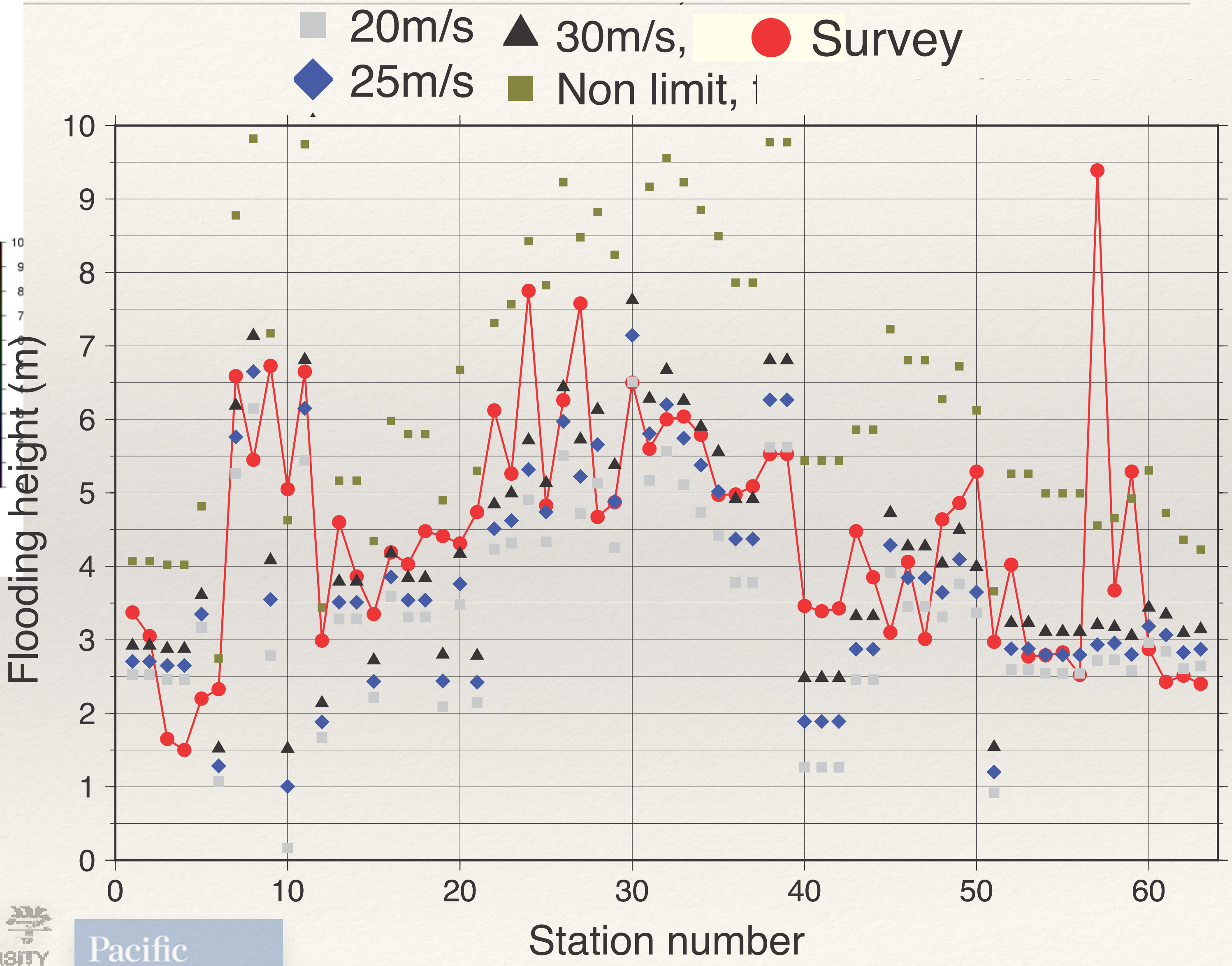
(c)
Wave2
Non–leveling off
Leveling off with 20m/s
Leveling off with 25m/s
Leveling off with 30m/s
Outside of bay
Hs (m)
24
22
20
18
16
14
12
10
8
6
4
2
0
12
11/07
00
12
11/08
00
Time (UTC)

Field survey data (Tajima et al. 2014)



Comparison of highest surge levels to field survey data





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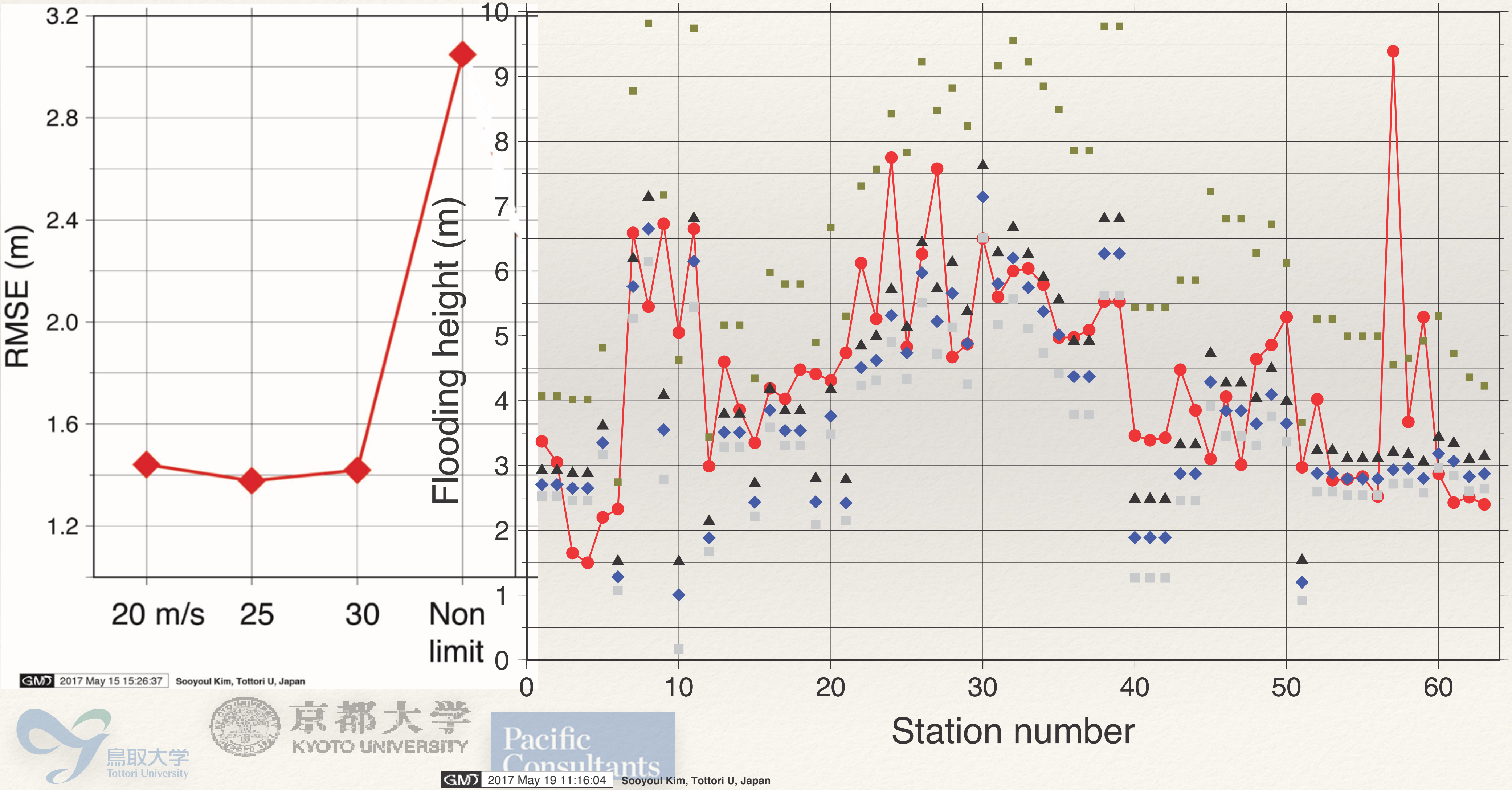
Comparison of highest surge levels to field survey data



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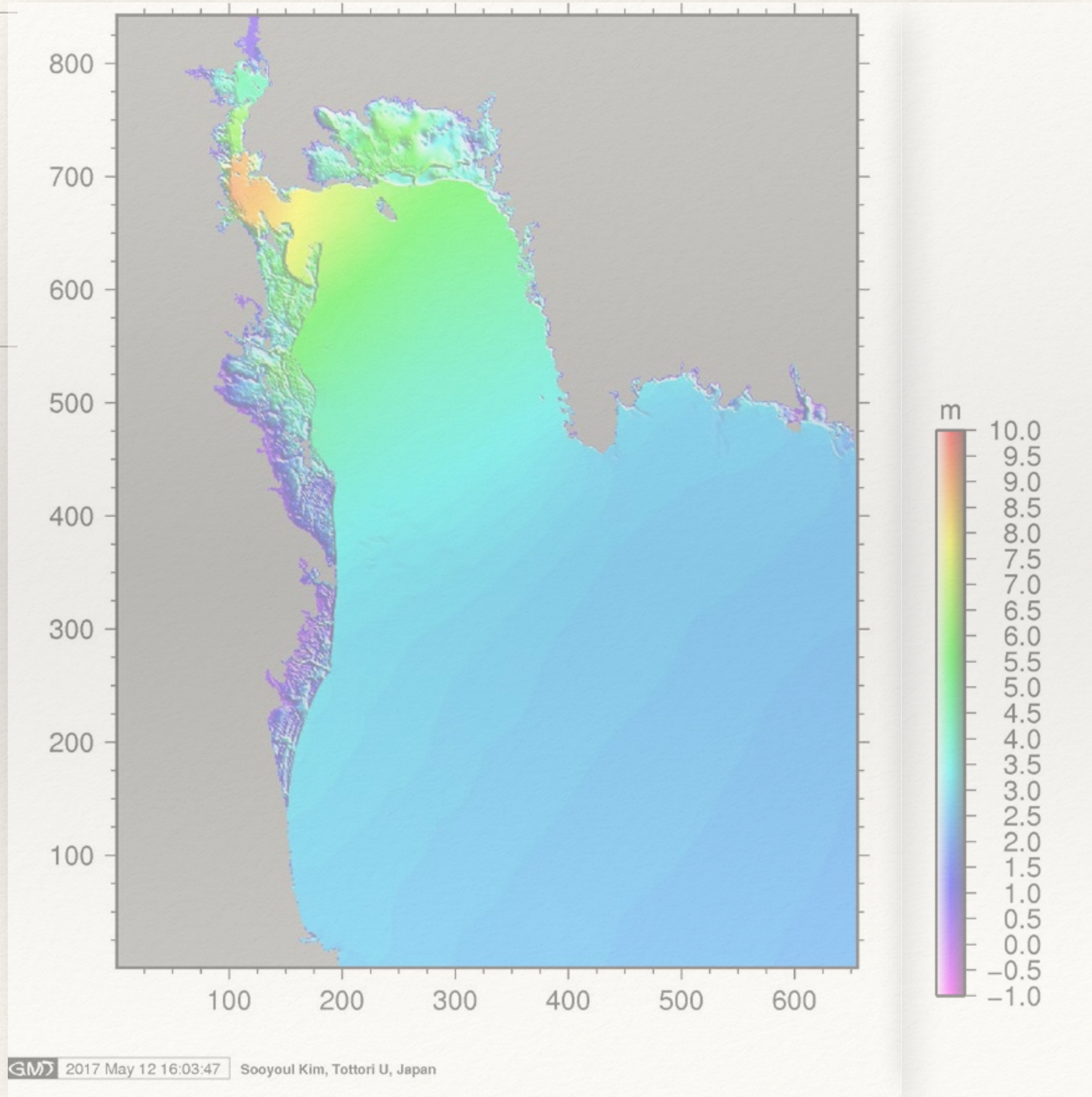
Other events



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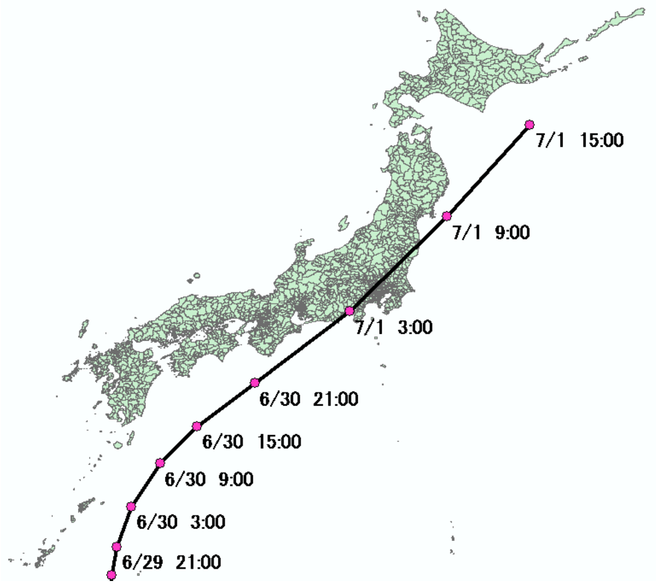
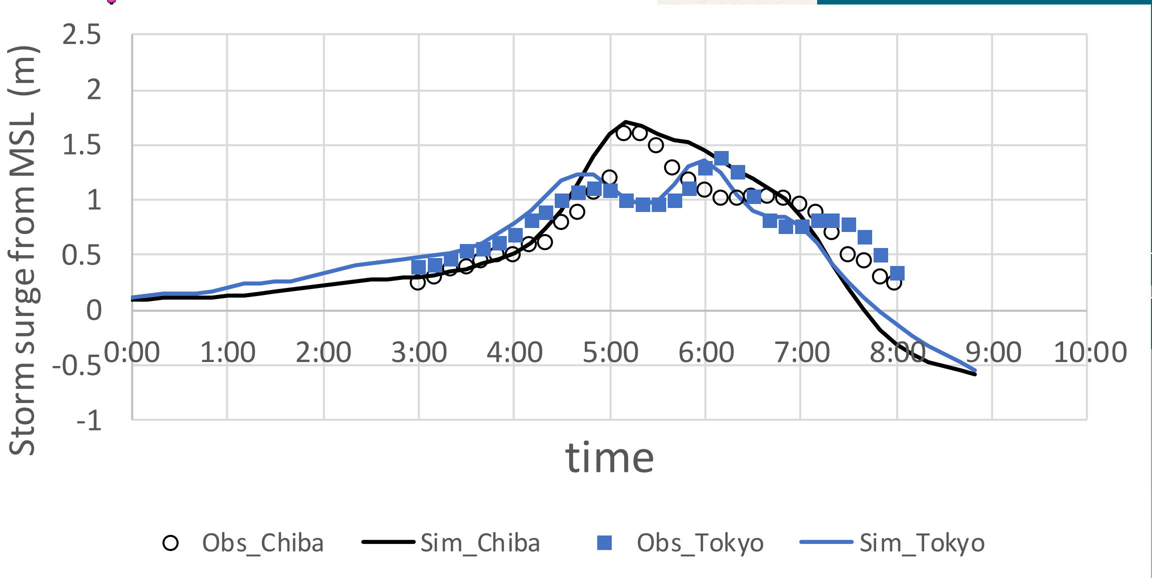
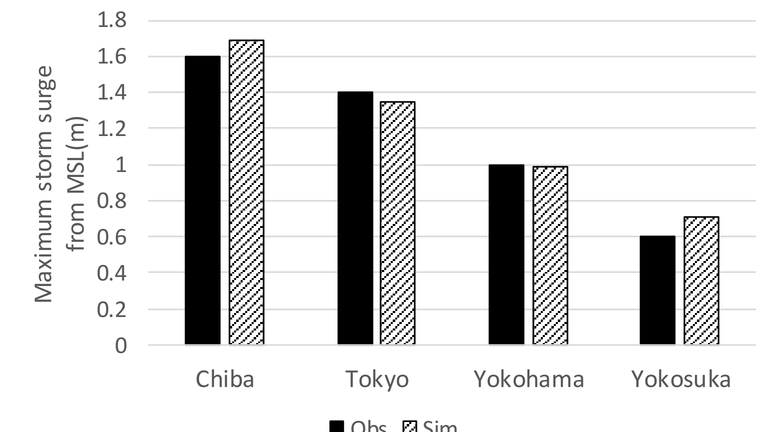
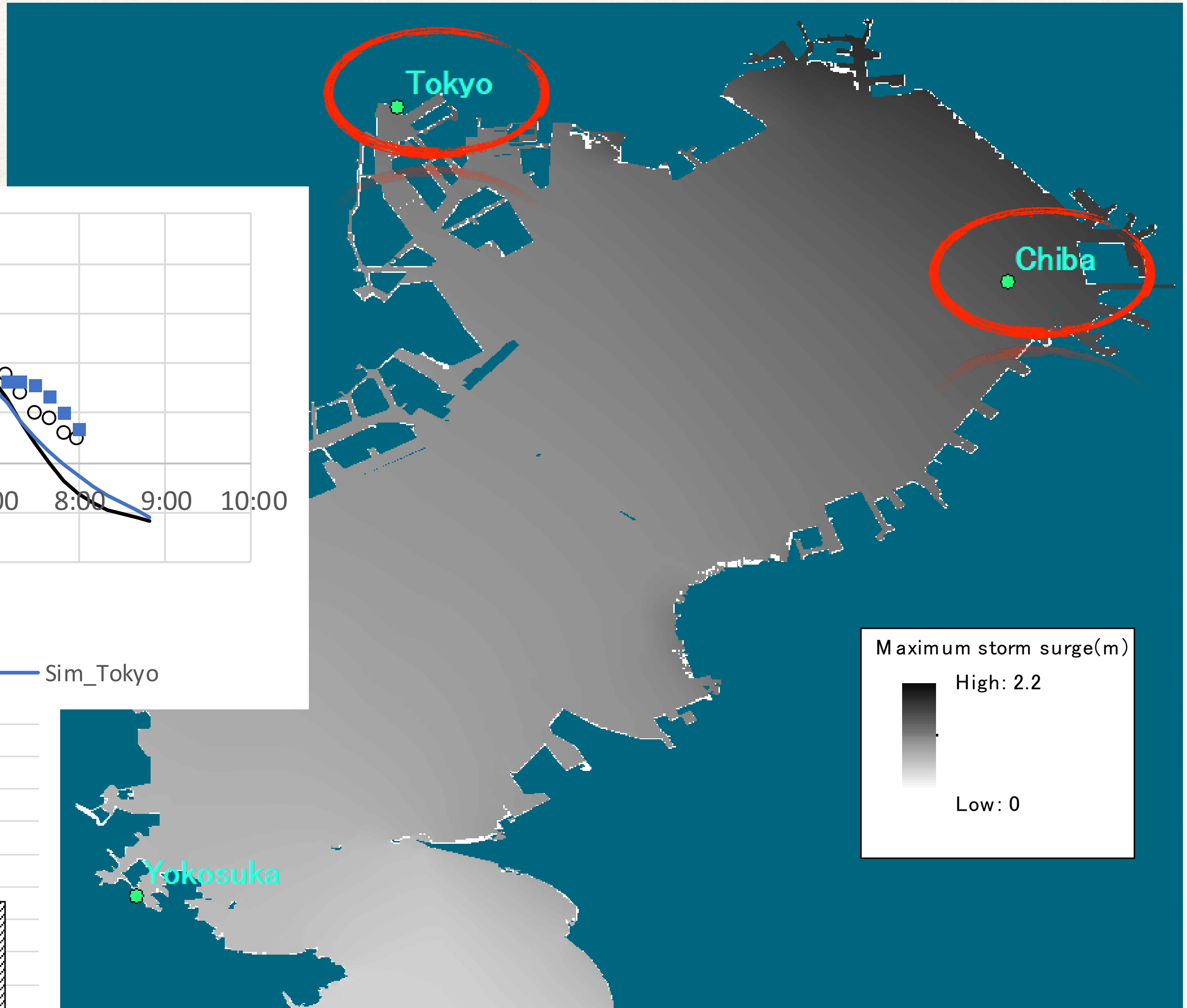
Typhoon Irma 1985 (25 m/s levelling off)

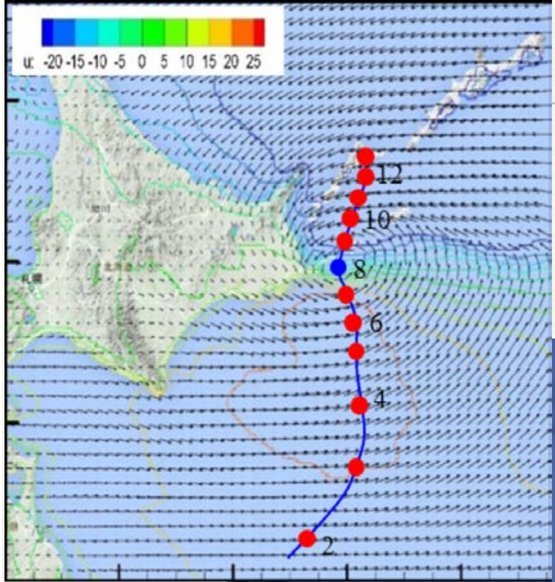




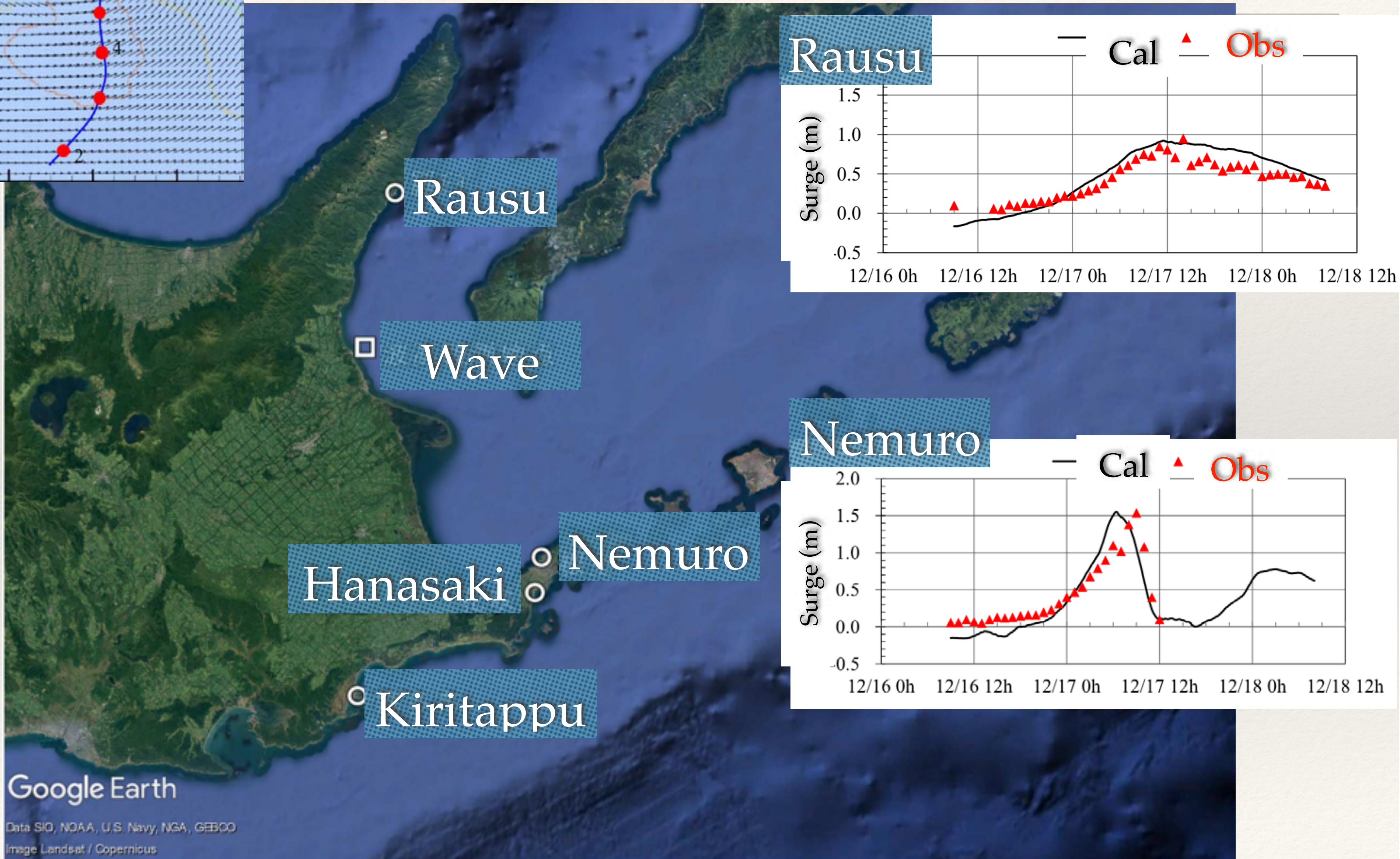




Hisamatsu et al. 2017

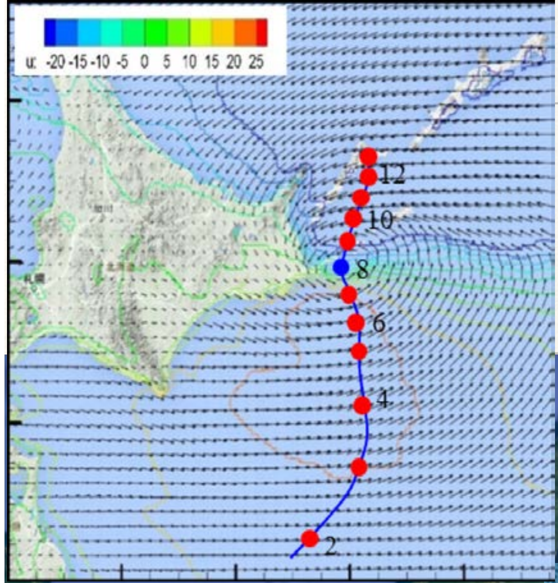


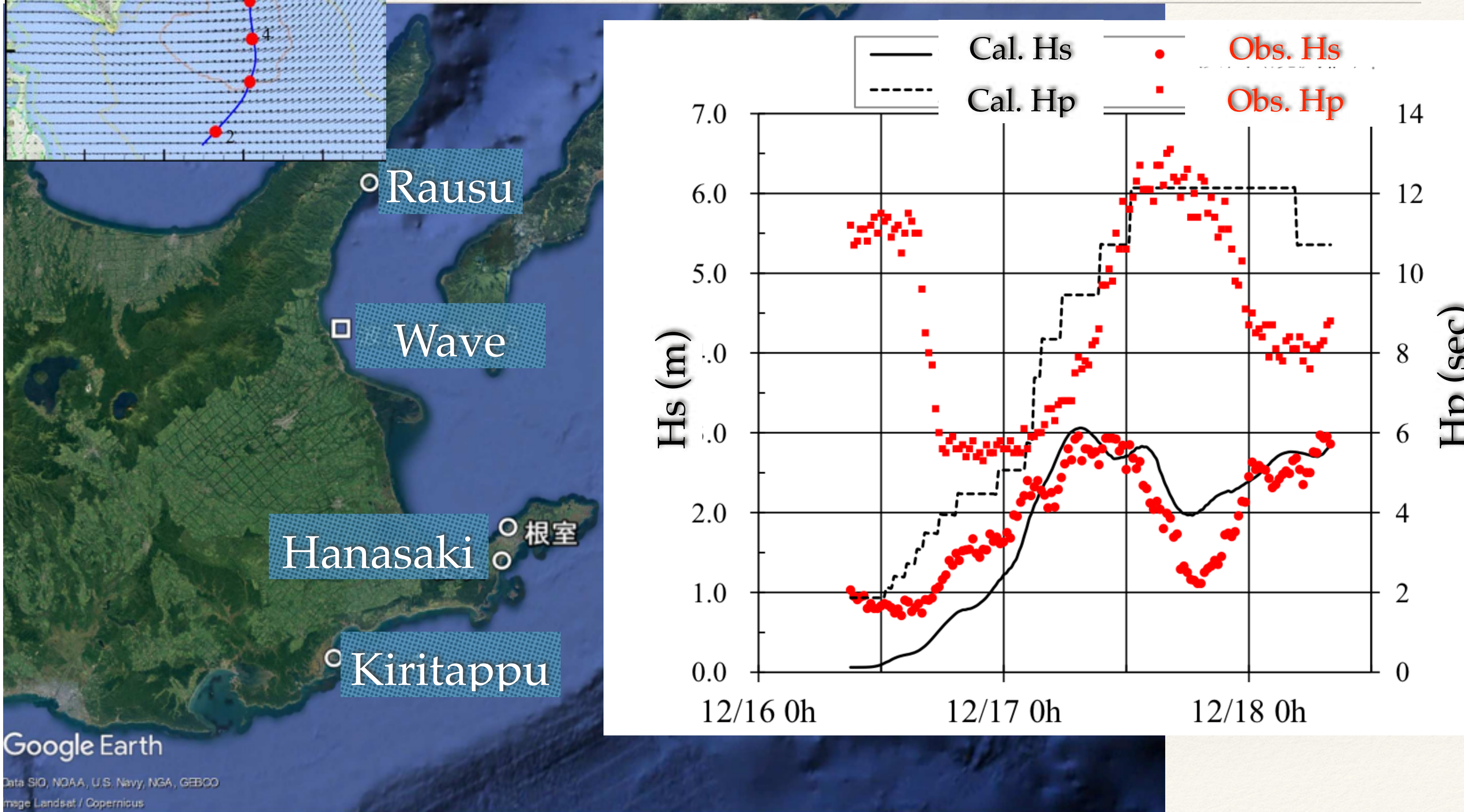
Low Pressure System 2014 in Hokkaido (25 m/s levelling off)



Kumagai et al. 2017

Low Pressure System 2014 in Hokkaido (25 m/s levelling off)





Kumagai et al. 2017

Further work

- Prove the idea in the exponential wave growth term physically for
    - waves,
    - surges and
    - any other physics
- under extreme events

Summary

- Using the step function, the wind speed-capped wave dependent C_d was estimated
- Wave-current interaction induced bottom f_c equivalent to approx. 0.02 of Manning Number
- Levelling off at 25-30 m/s was proper
- It is validated by Typhoon Haiyan surges using
  - wind speed-capped wave dependent C_d &
  - wave-current interaction induced bottom f_c
- Validate time series of waves and surges using the present method for
  - Typhoon Irma 1985 in Tokyo,
  - Low Pressure System 2014 in Hokkaido

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Questions or comments ?

Thank you very much