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The State of the Art and Science of Coastal Engineering

Numerical Study on Accumulation Mechanism of Coral Gravels around Ballast Island, the Coral Cay off the Coast of Iriomote Island

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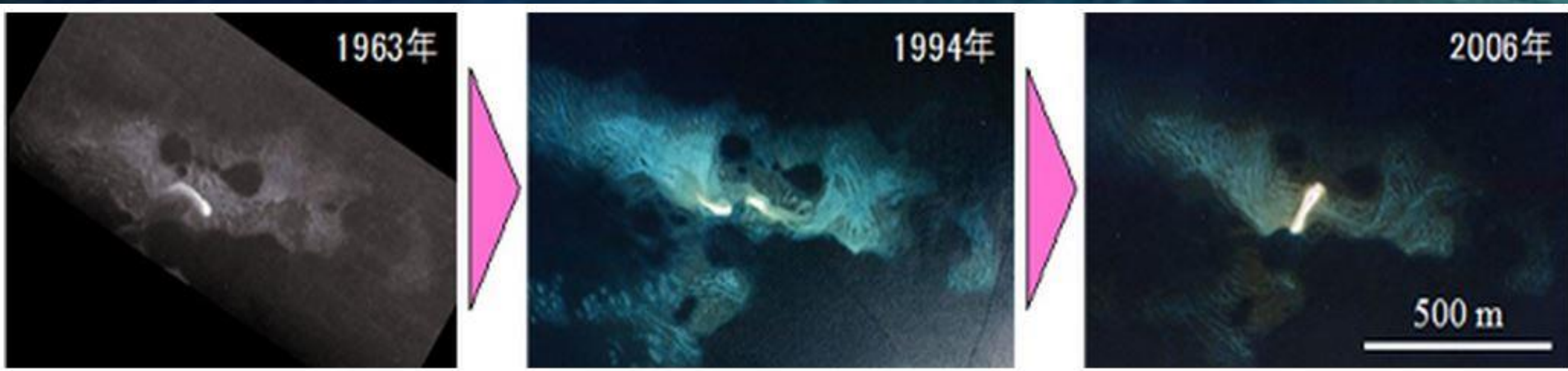
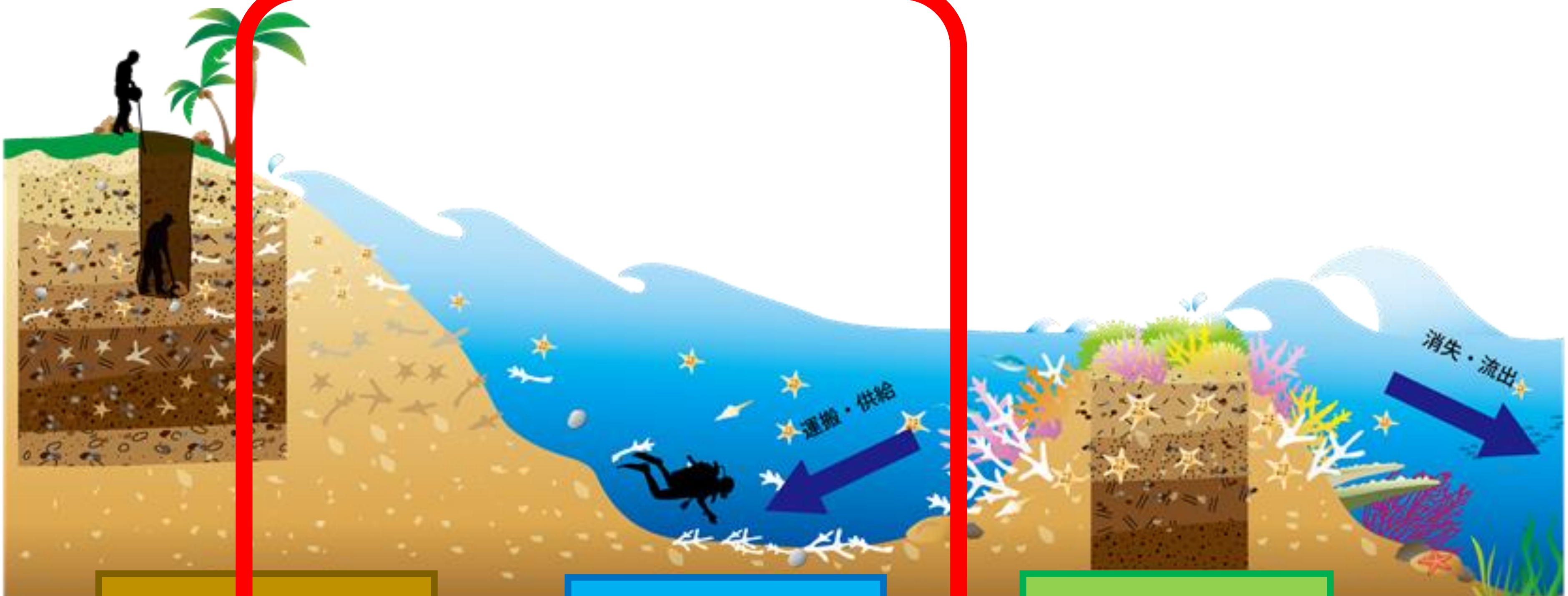
Background

- Ballast island is a coral cay formed on isolated coral reef.
- While this coral cay frequently alters its shape, accumulated coral gravels have kept forming the cay for more than 50 yrs.
- Understanding/modeling of transport of coral gravels & formation of coral cays may be of importance for better protection & conservation strategies of a coral coast.

Ballast island (Iriomote-island, Japan)



Protection Concept of Coral Beach

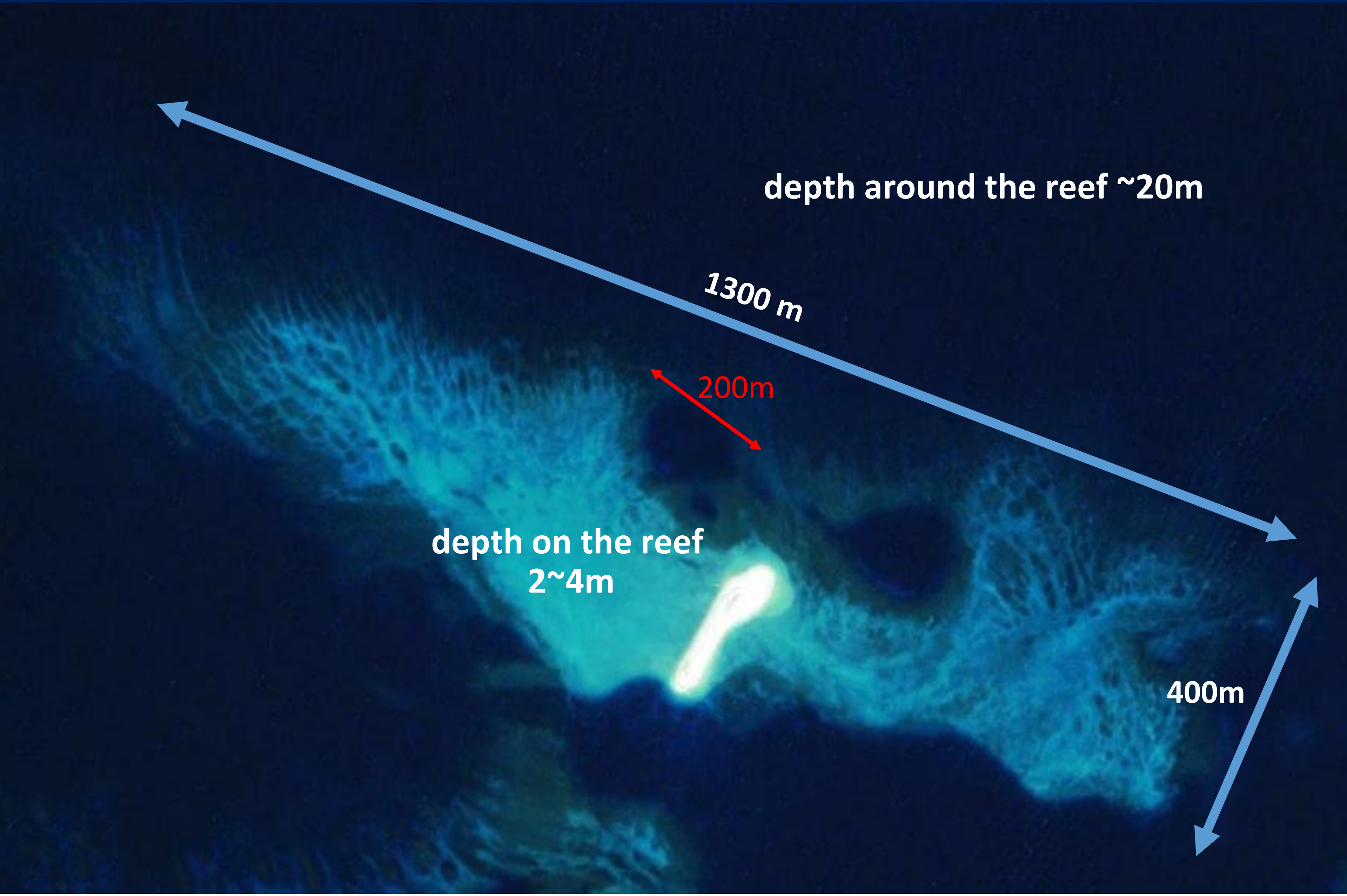


Deposition

Transport

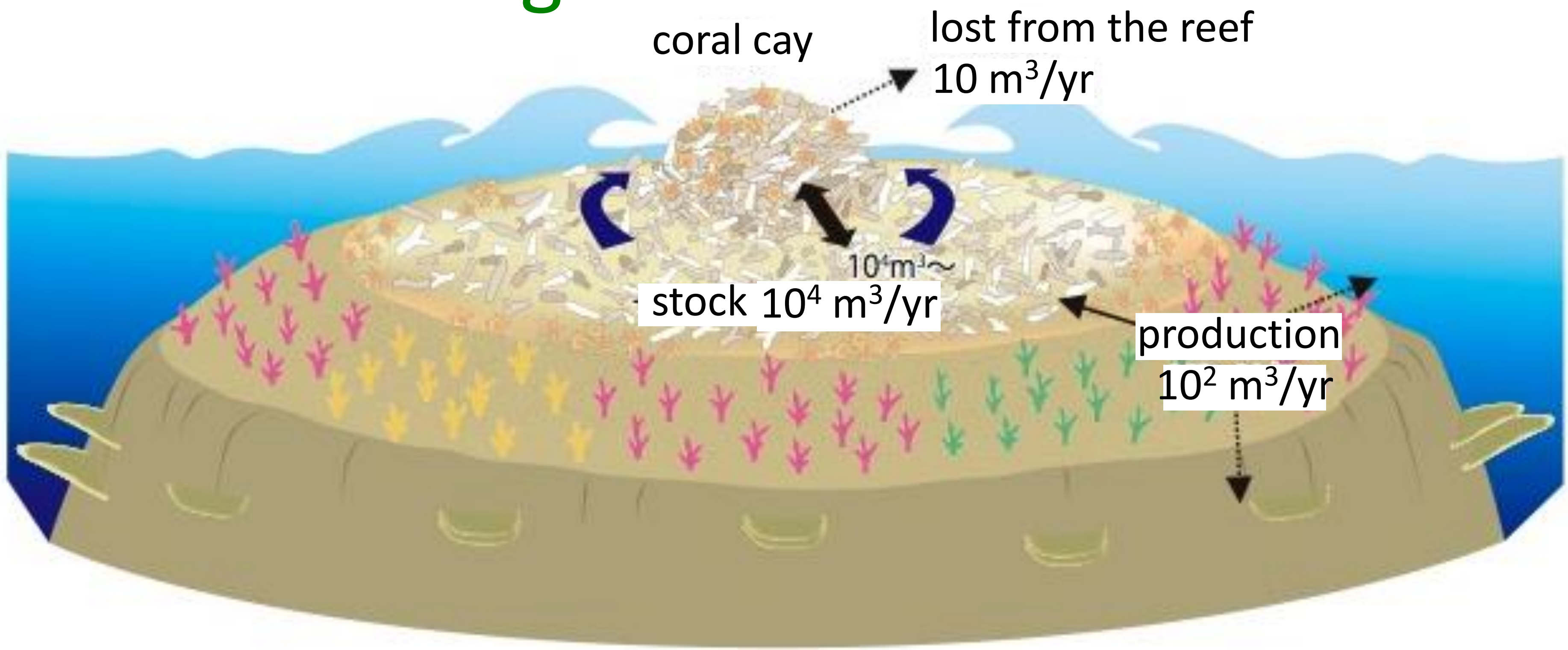
Supply

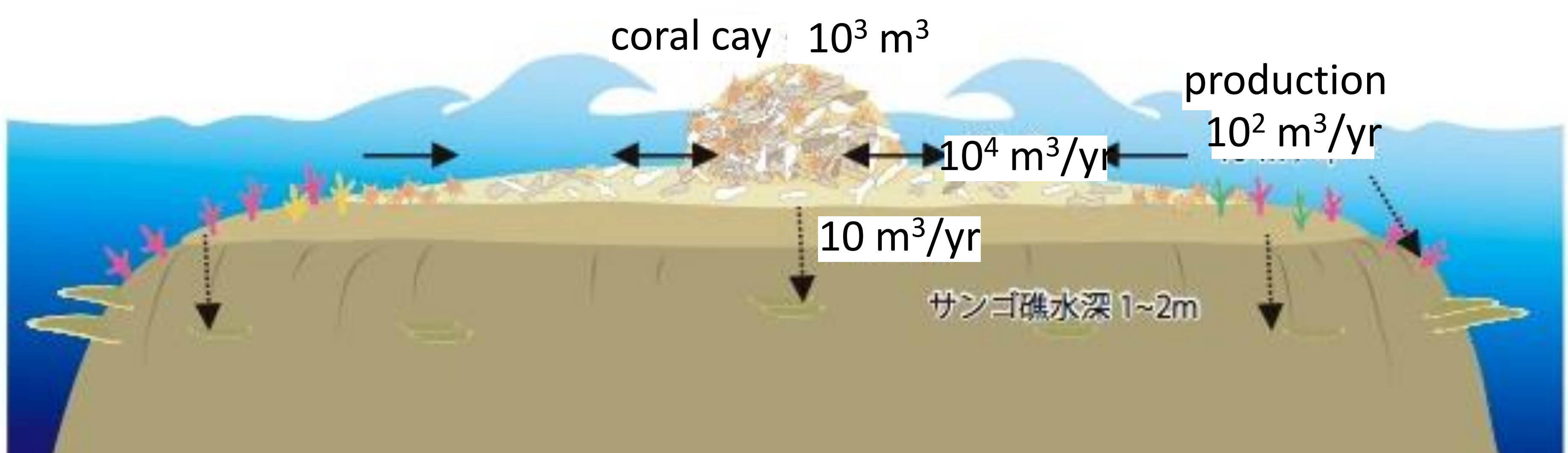
How was Ballast Island formed?



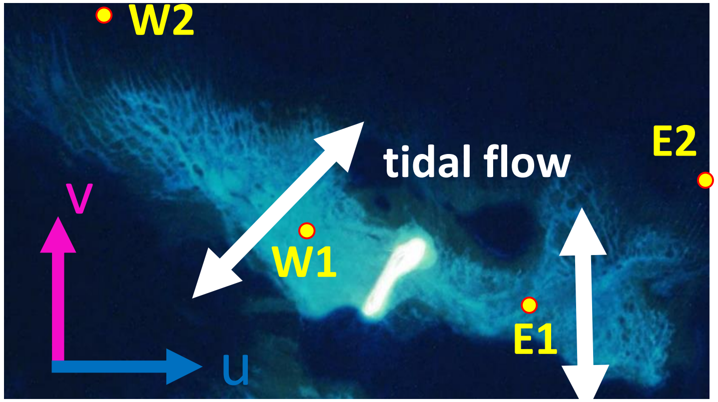
How was Ballast Island formed?

Budget of Coral Gravels

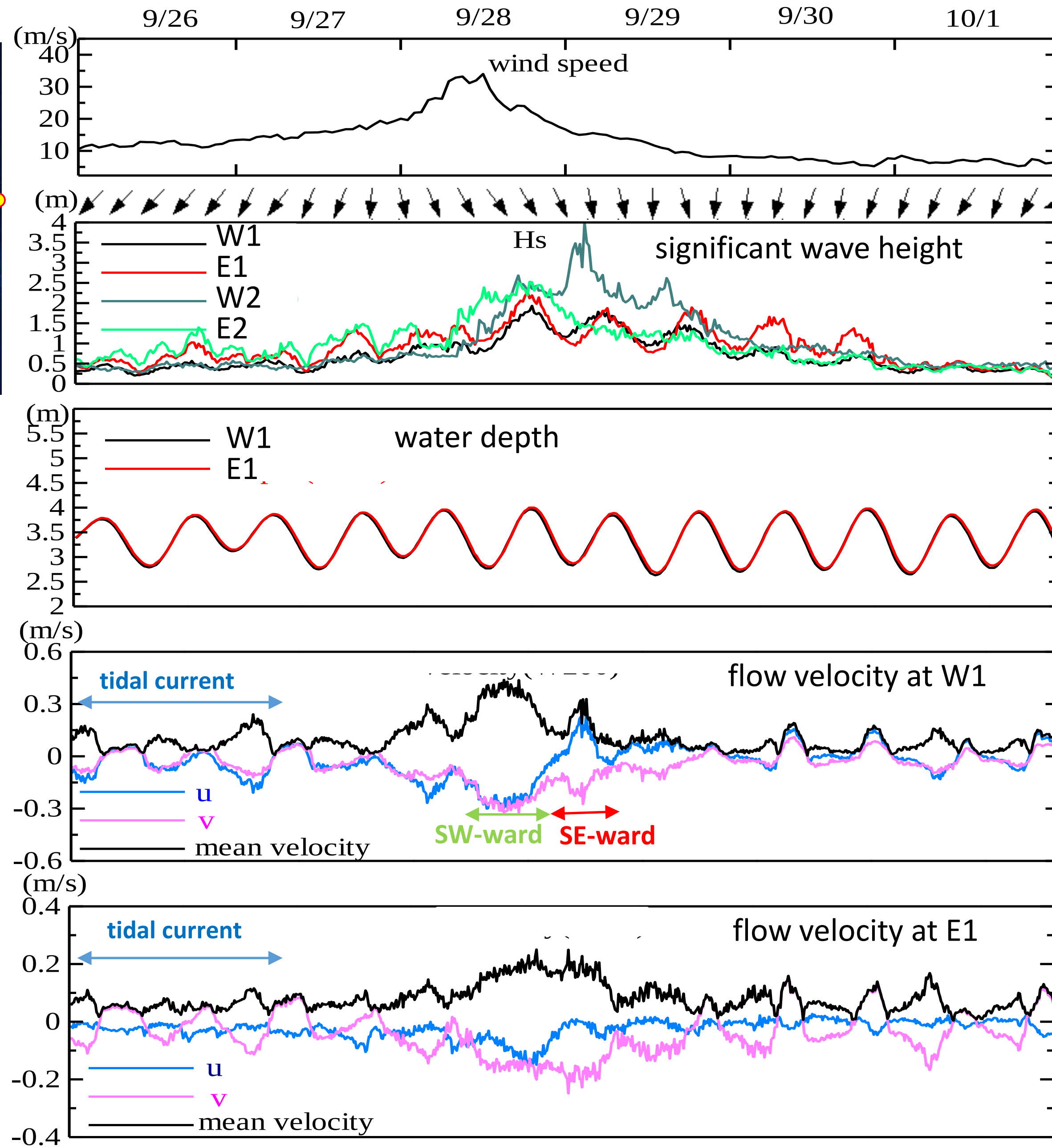




Field Survey (1)

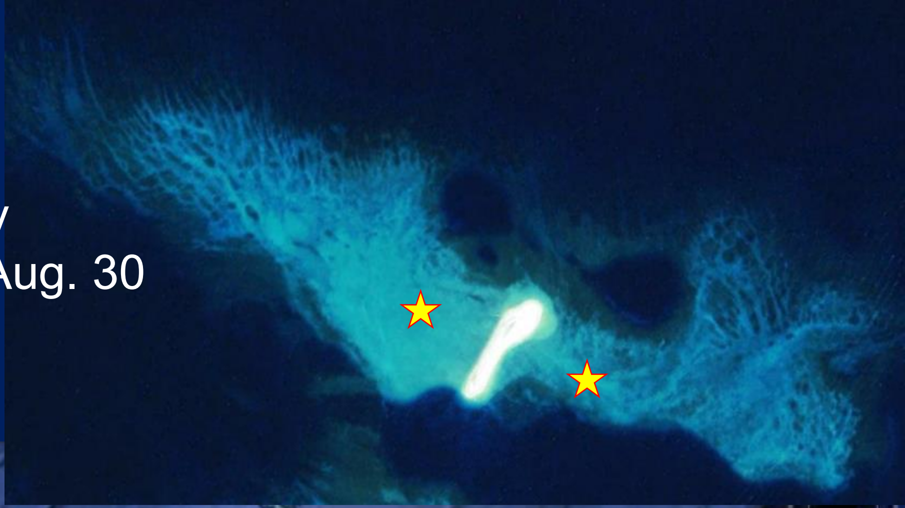


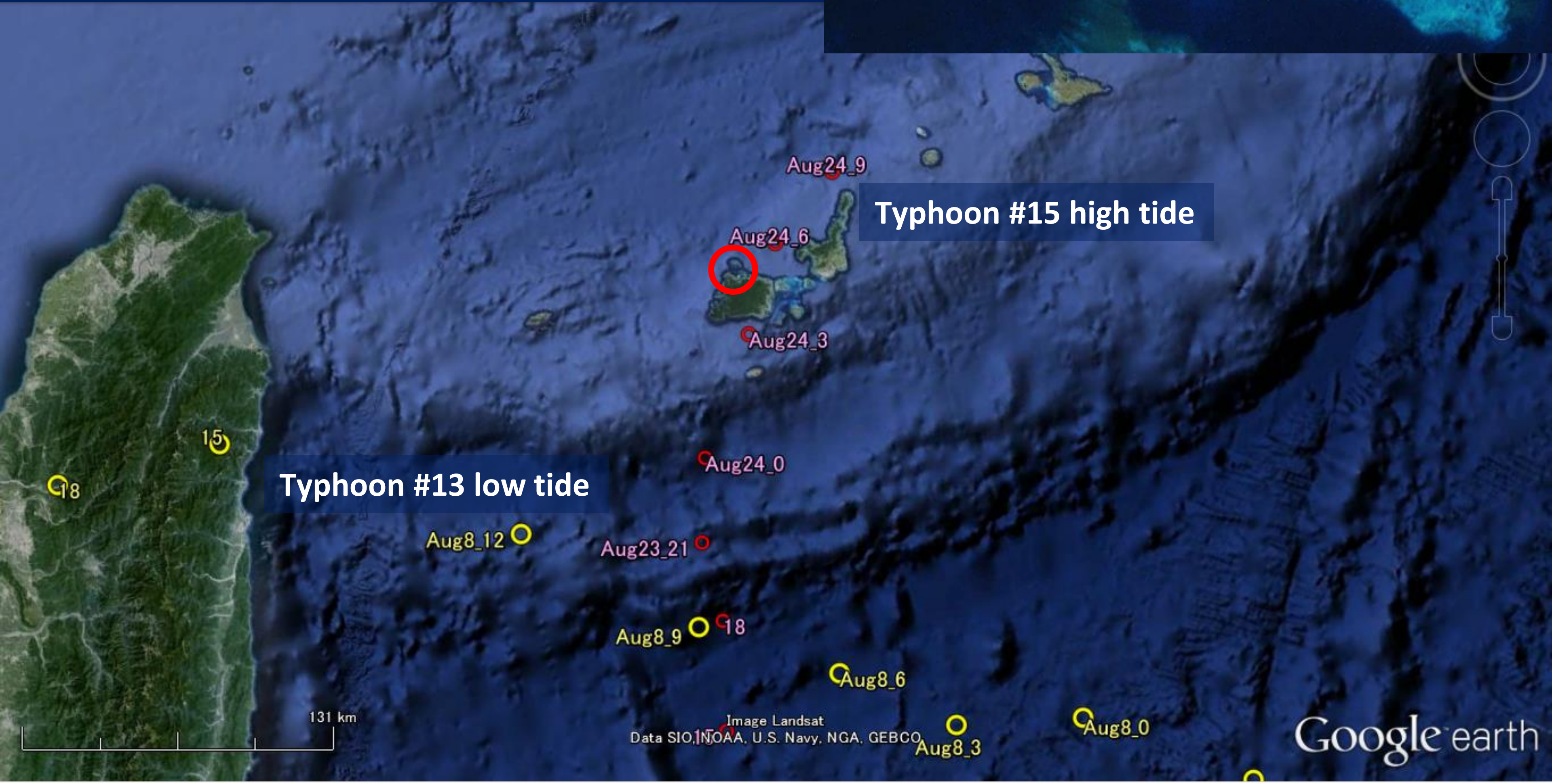
- Wave height on the reef is affected by tide level.
- Dominant wave direction is ENE.
- Waves from NW can be generated under typhoon.
- Tidal current is dominant under mild waves.
- Wave-induced current is dominant during the storm.
- Tidal current direction is N-S



Field Survey (2)

Tracer survey (colored local coral gravels)
placed on Jul. 30, 2015 at both side of the cay
Tracer survey were conducted on Aug. 14 & Aug. 30
Typhoon #13 hit the site on Aug.6
Typhoon #15 hit the site on Aug.24



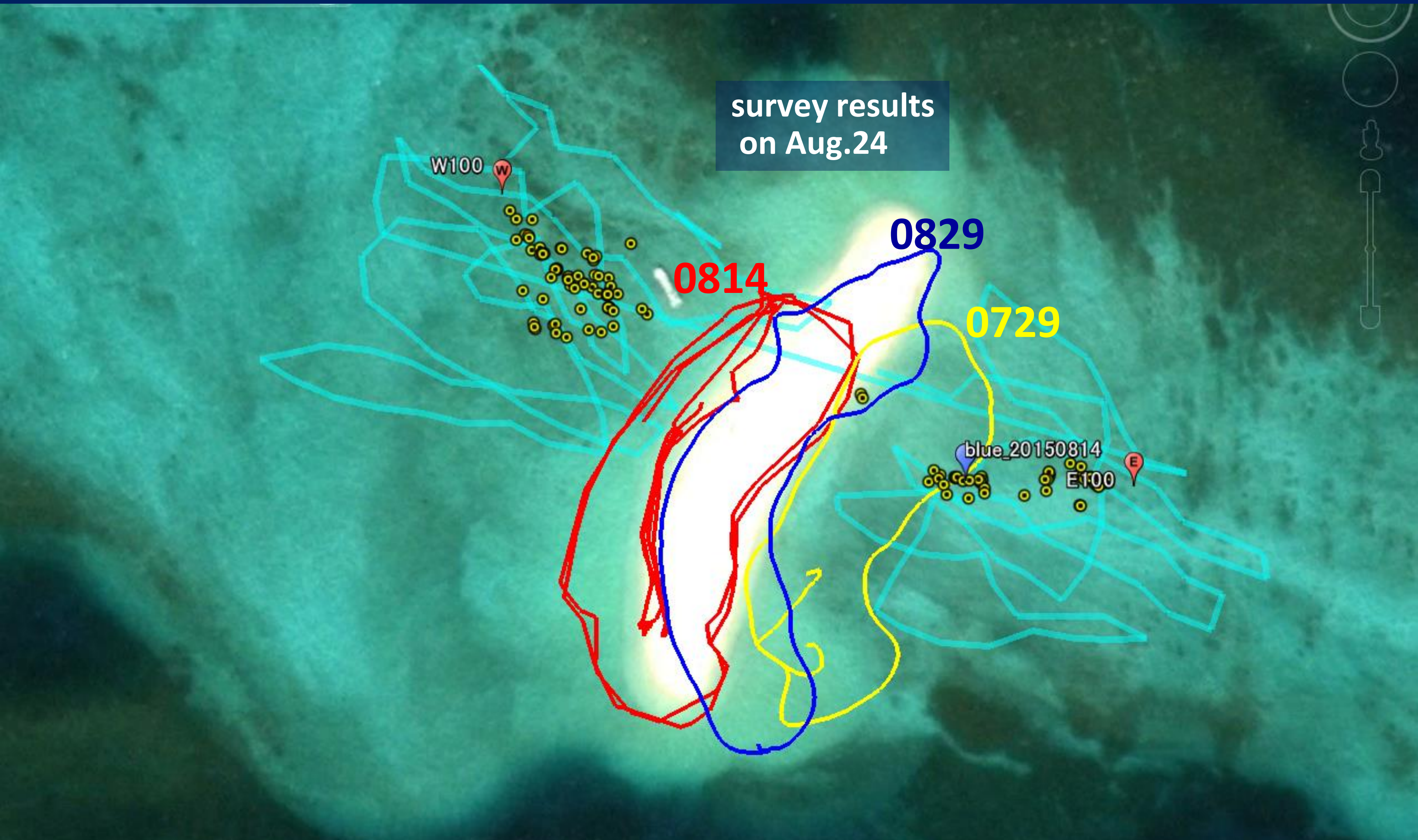


Field Survey (2)

Tracer survey were conducted on Aug. 14 & Aug. 30

Typhoon #13 hit the site on Aug.6 ⟶ no significant movement except some on the east

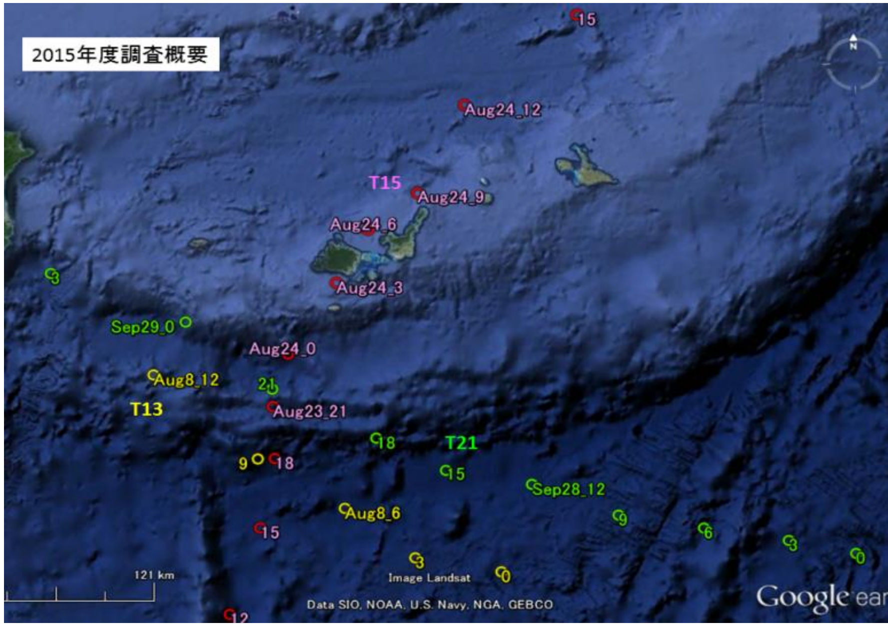
Typhoon #15 hit the site on Aug.24 ⟶ toward cay from the both side

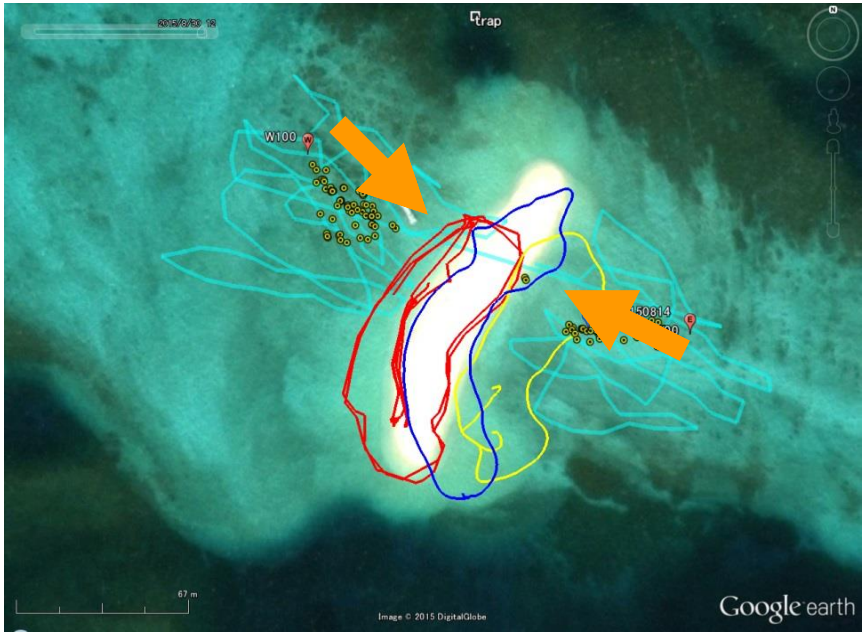


Findings of the Field Survey

Field Survey

- Waves & current on the reef
- Monitoring of cay morphology
- Tracing of colored gravels
- Pressure under the gravel bed





- Wave dominantly determines the gravel transport
- Colored gravels on both sides of the cay moved toward the cay
- Dominant wave direction induced by typhoon determine growth / collapse of the cay.
- Cay crest is largely lowered by the overtopping waves.
- Cay is developed around the swash zone and location of swash zone changes with tide level.

Two Primary Factors for Formation of Stable Cays

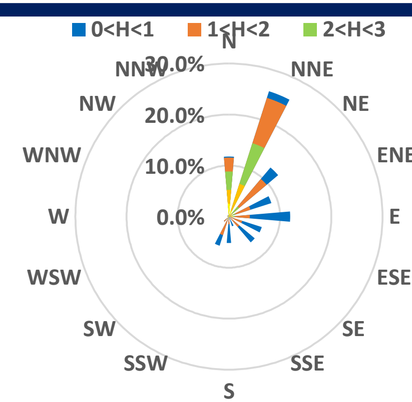
1. Coral gravels on the reef is transport and accumulate at certain location on the reef.

2. Accumulated gravels form cay higher than the high water level.

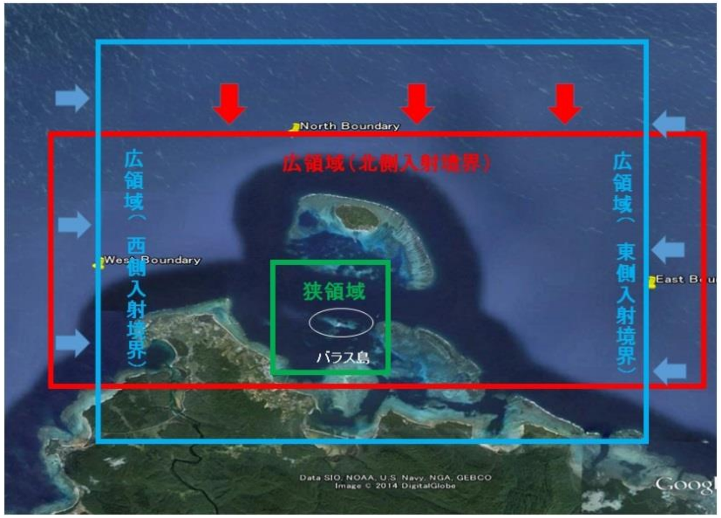
→ This study developed two separate models.

1. Large scale model (1)

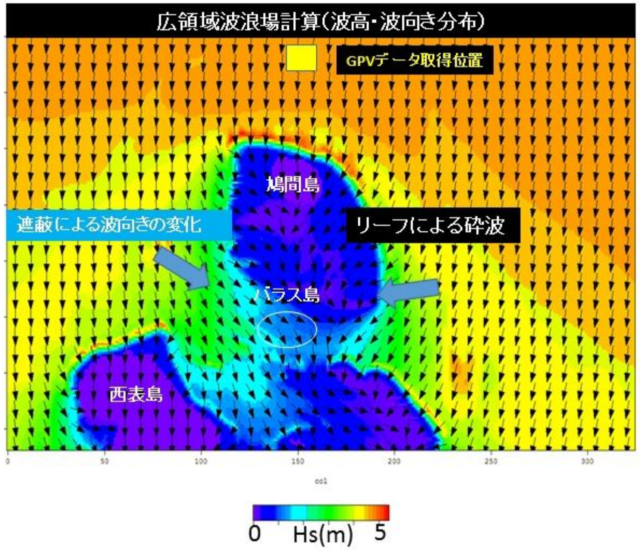
wave:	Energy balance equation
Current:	tide, wave-induced current
transport:	bedload model(Madsen, 1993) accounting for bed slope



1. Offshore waves were randomly selected based on the probability dist. of GPV wave data near the site.
2. Under each wave, coral transport was computed for an hour.
3. Iterate the same process with different wave conditions.



Computation domain



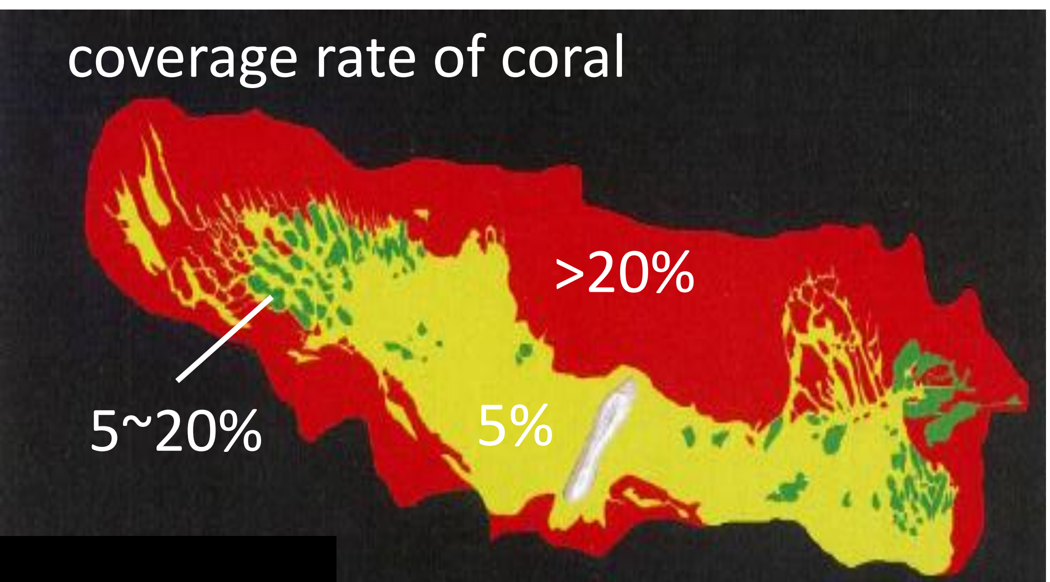
wave computation

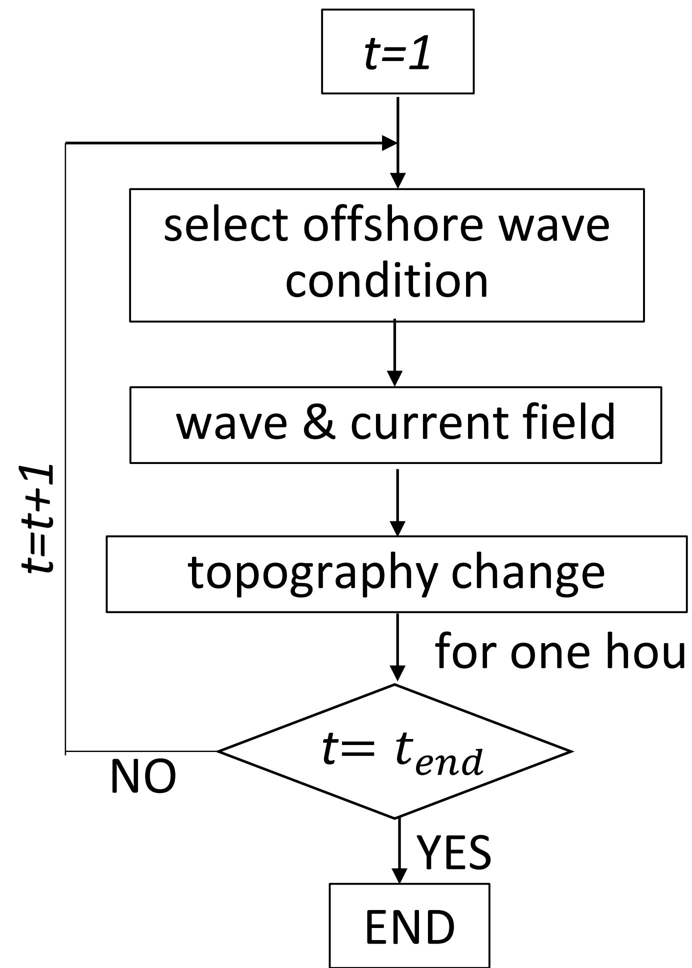
Large scale model (2)

$$\begin{pmatrix} q_{SB,nl} \\ q_{SB,\beta} \\ q_{SB,nl} \end{pmatrix} = \frac{\delta_s}{\delta_0} \begin{pmatrix} 2\mu_{nl} \\ -4.5\mu_b \\ 6\mu_c \end{pmatrix} \frac{1}{(\rho_s - \rho)g} \left(\frac{\tau_{wm}}{\rho} \right)^{\frac{3}{2}}$$

$$\mu_{nl} = 2\left(\frac{u_c}{U_b} - 0.5 \right) \qquad \mu_b = \frac{\tan \beta}{\tan \emptyset_m} \qquad \mu_c = \frac{|\tau_{cb}|}{\tau_{wm}}$$

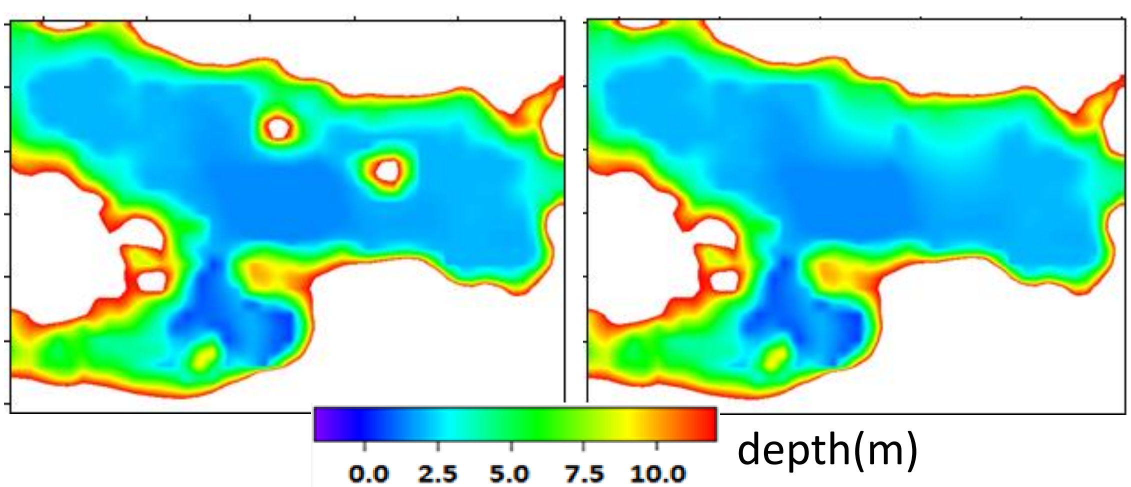
δ_s: thickness of the layer of accumulated coral gravels
δ_0: initial thickness of δ_s (=0.15 m)

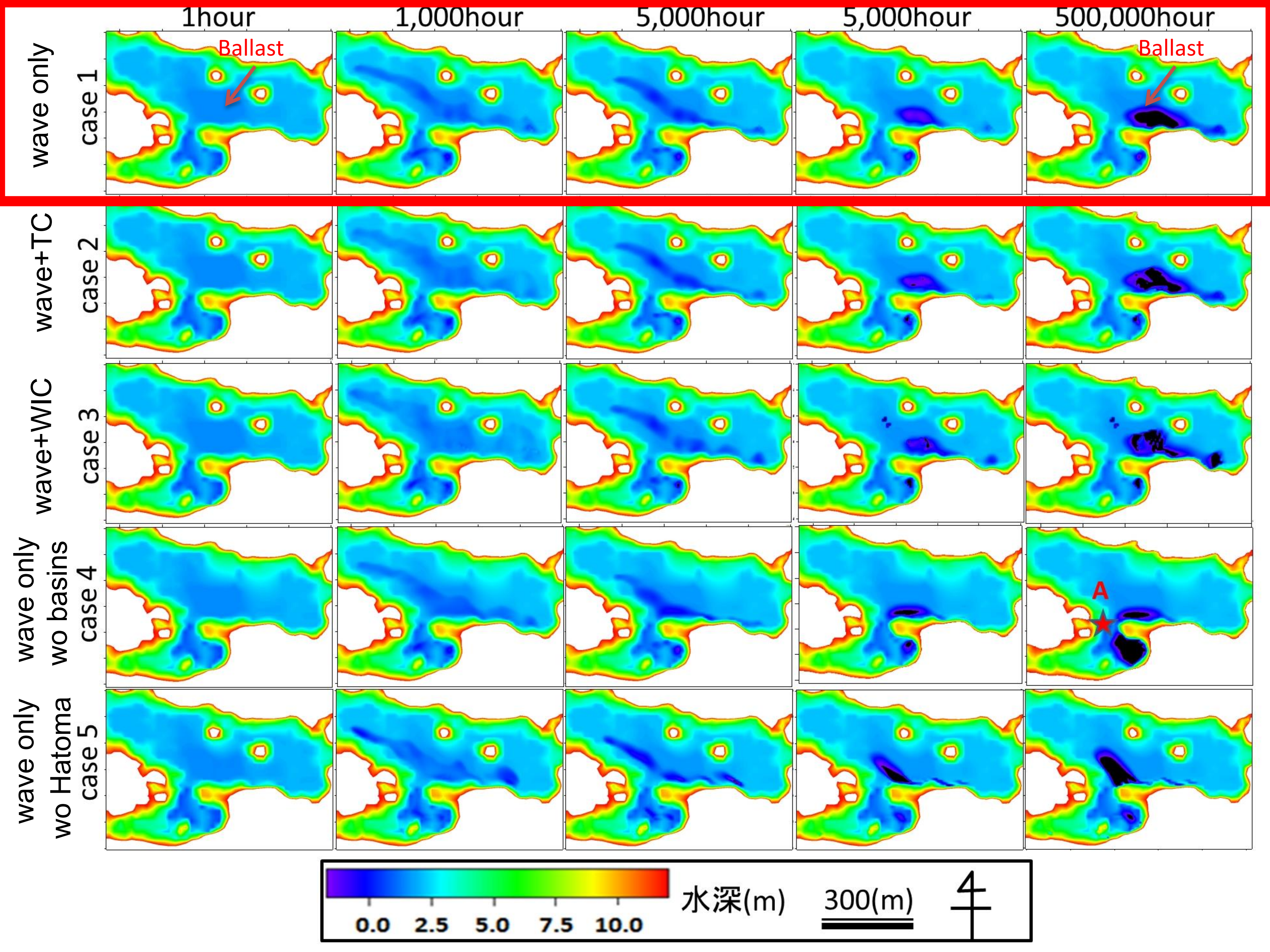




Large scale model (3)

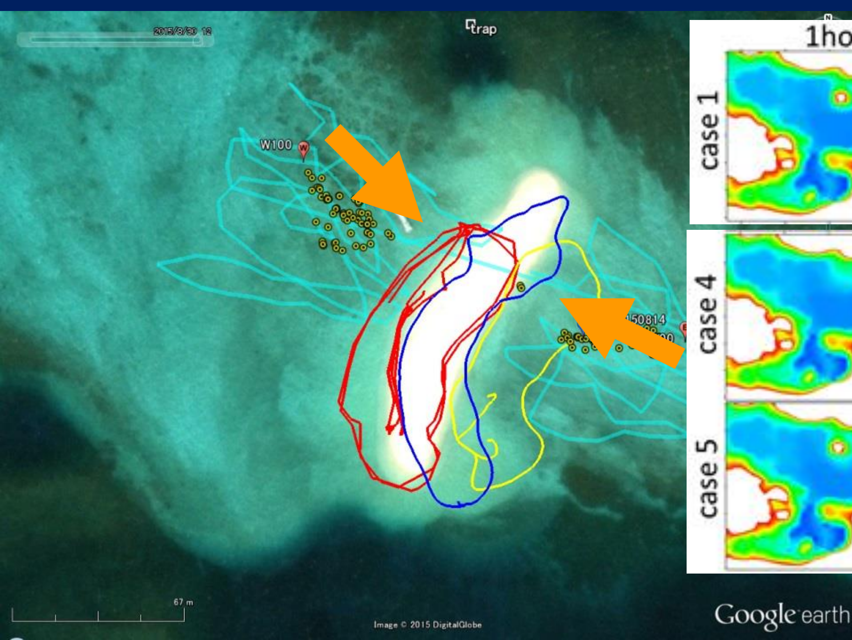
case	wave	tidal current	wave-induced current	deep holes	Hatoma Island
1	○	×	×	○	○
2	○	○	×	○	○
3	○	×	○	○	○
4	○	×	×	×	○
5	○	×	×	○	×

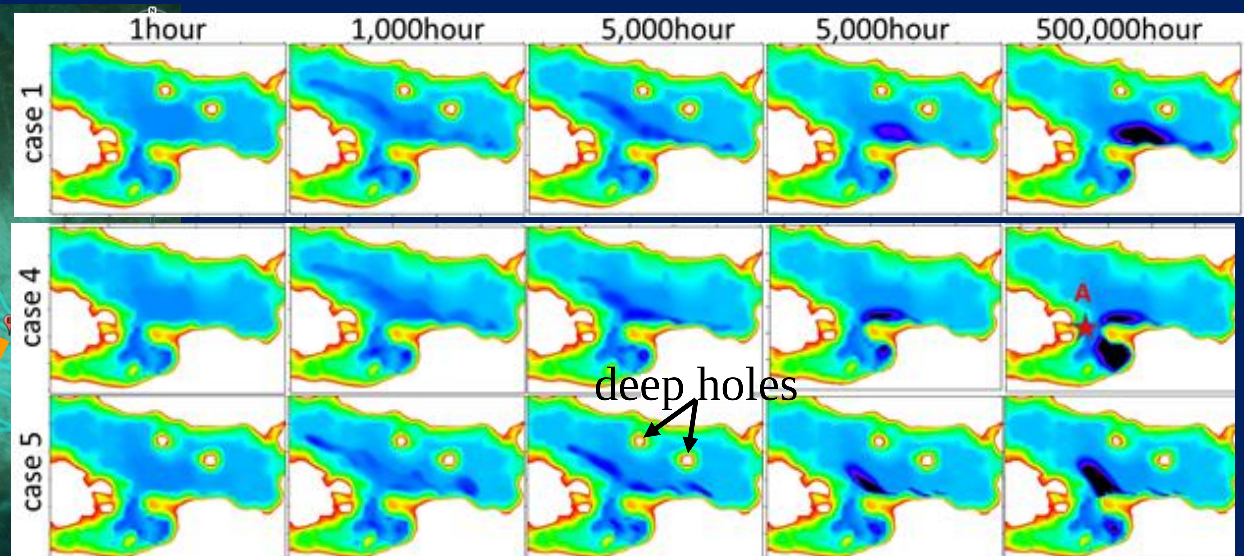



1hour
1,000hour
5,000hour
5,000hour
500,000hour
wave only
case 1
Ballast
Ballast
wave+TC
case 2
wave+WIC
case 3
wave only
wo basins
case 4
A
wave only
wo Hatoma
case 5
0.0
2.5
5.0
7.5
10.0
水深(m)
300(m)

Summary

- Tracer survey of coral gravels showed that gravels on both side of the Ballast island are transported toward the island.
- Wave-induced transport has a dominant role to accumulate coral gravels around Ballast island.
- Both Hatoma island and deep holes on the reef appear to have significant influence on accumulation of coral gravels.





Next step?

1. Coral gravels on the reef is transport and accumulate at certain location on the reef.
2. Accumulated gravels form cay higher than the high water level.

➡ This study developed two separate models.

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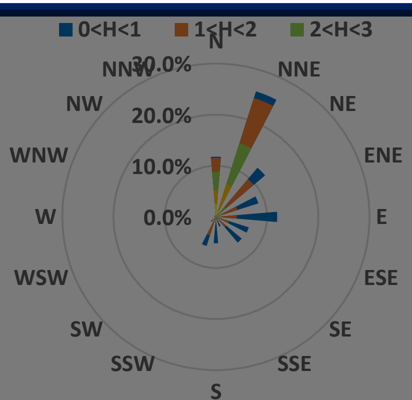

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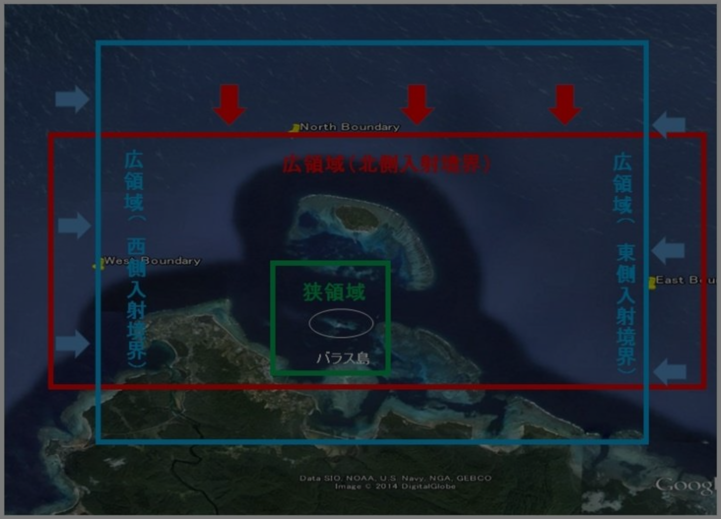
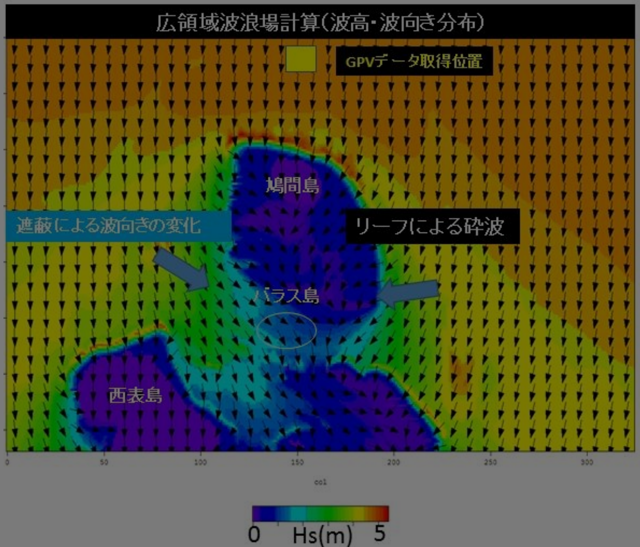
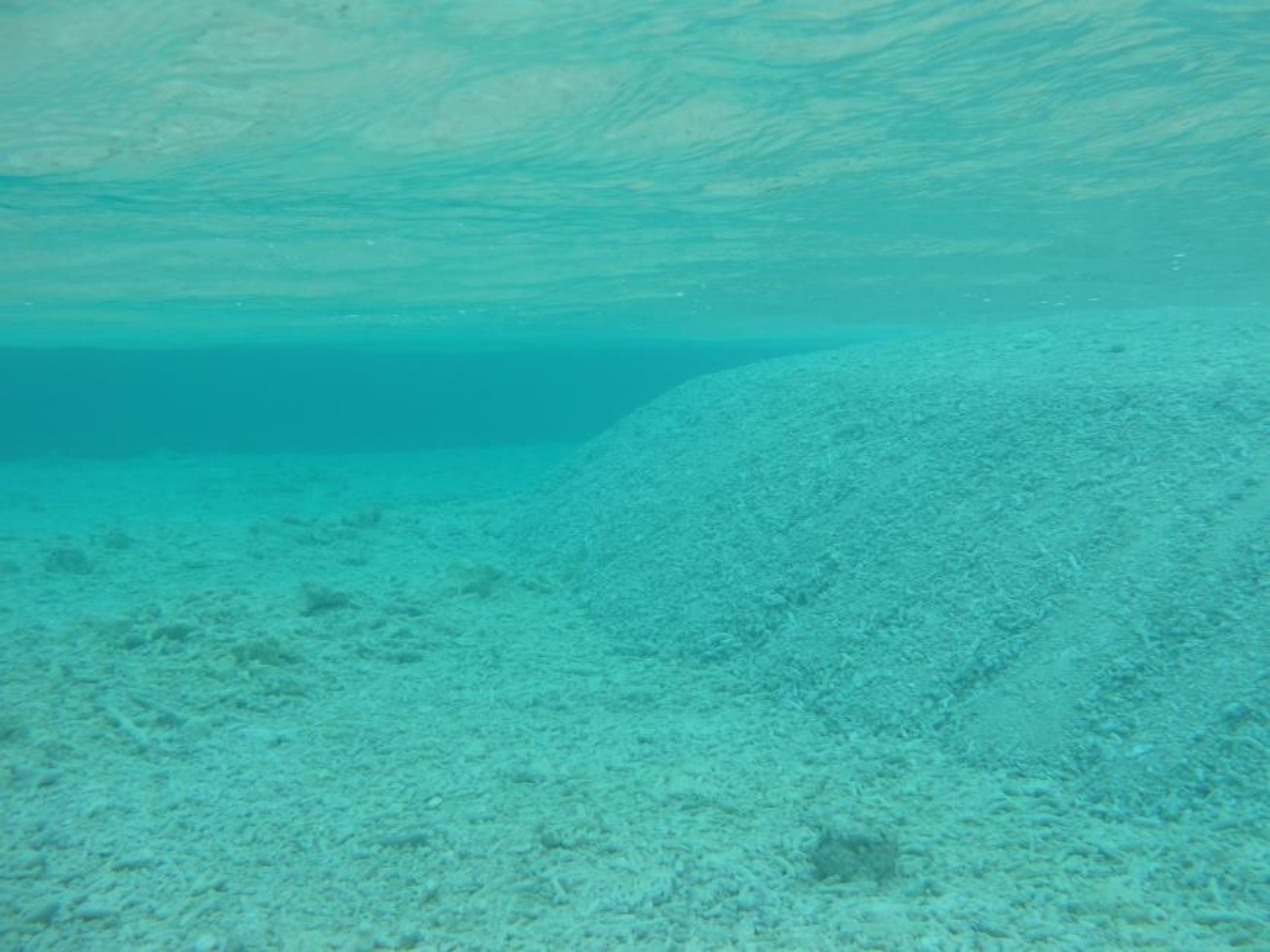


Computation domain

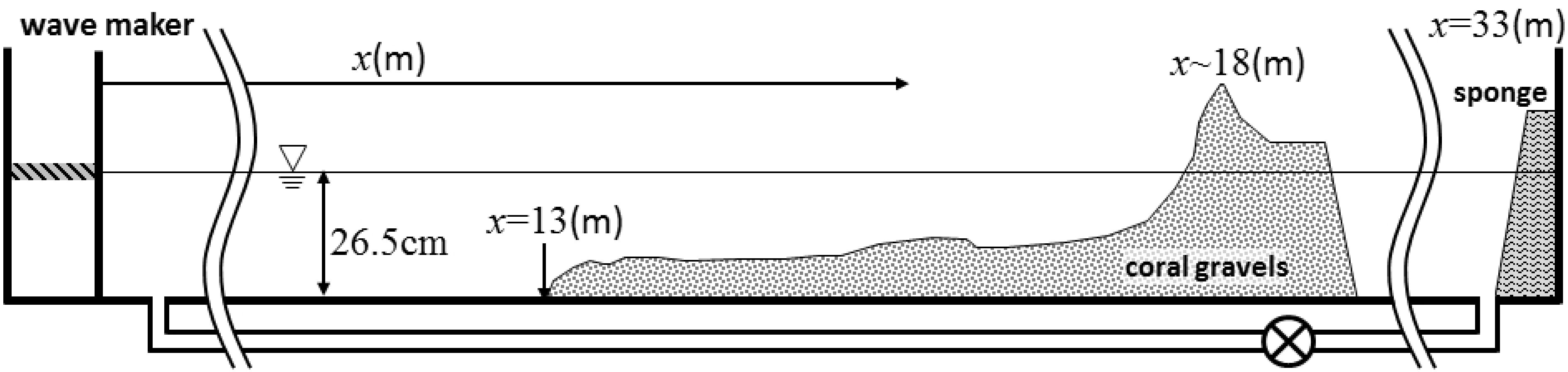


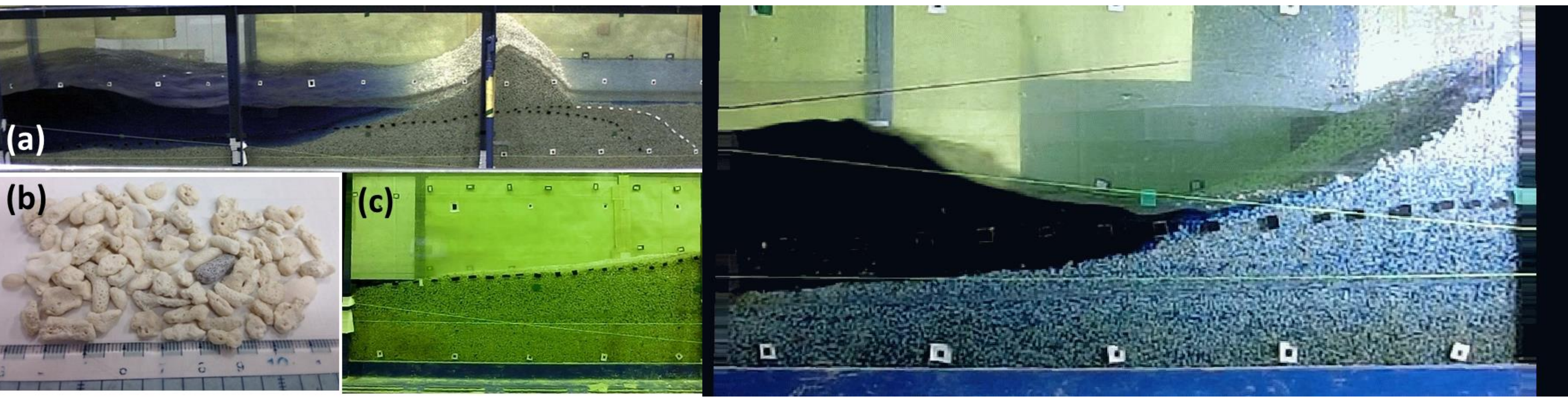
wave computation

Behavior around the swash zone



Laboratory Experiment

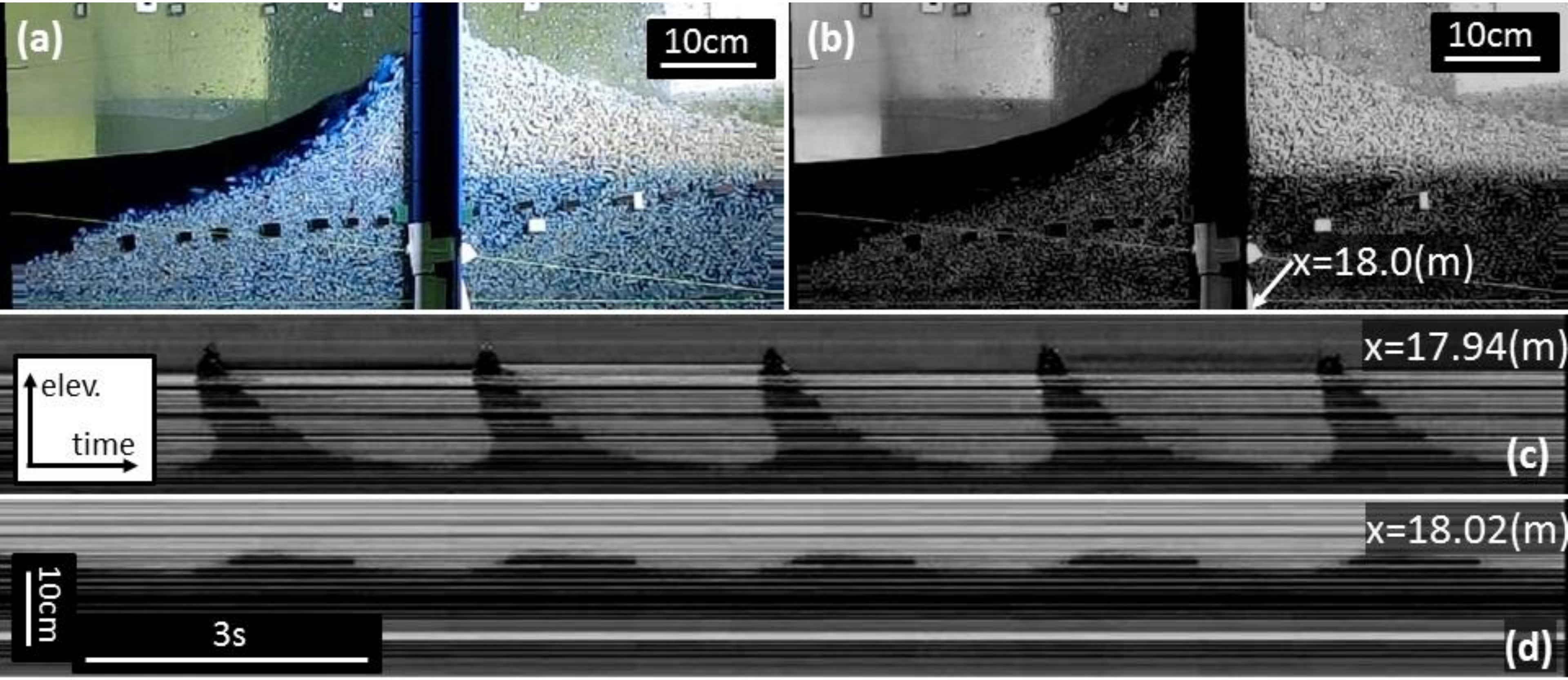




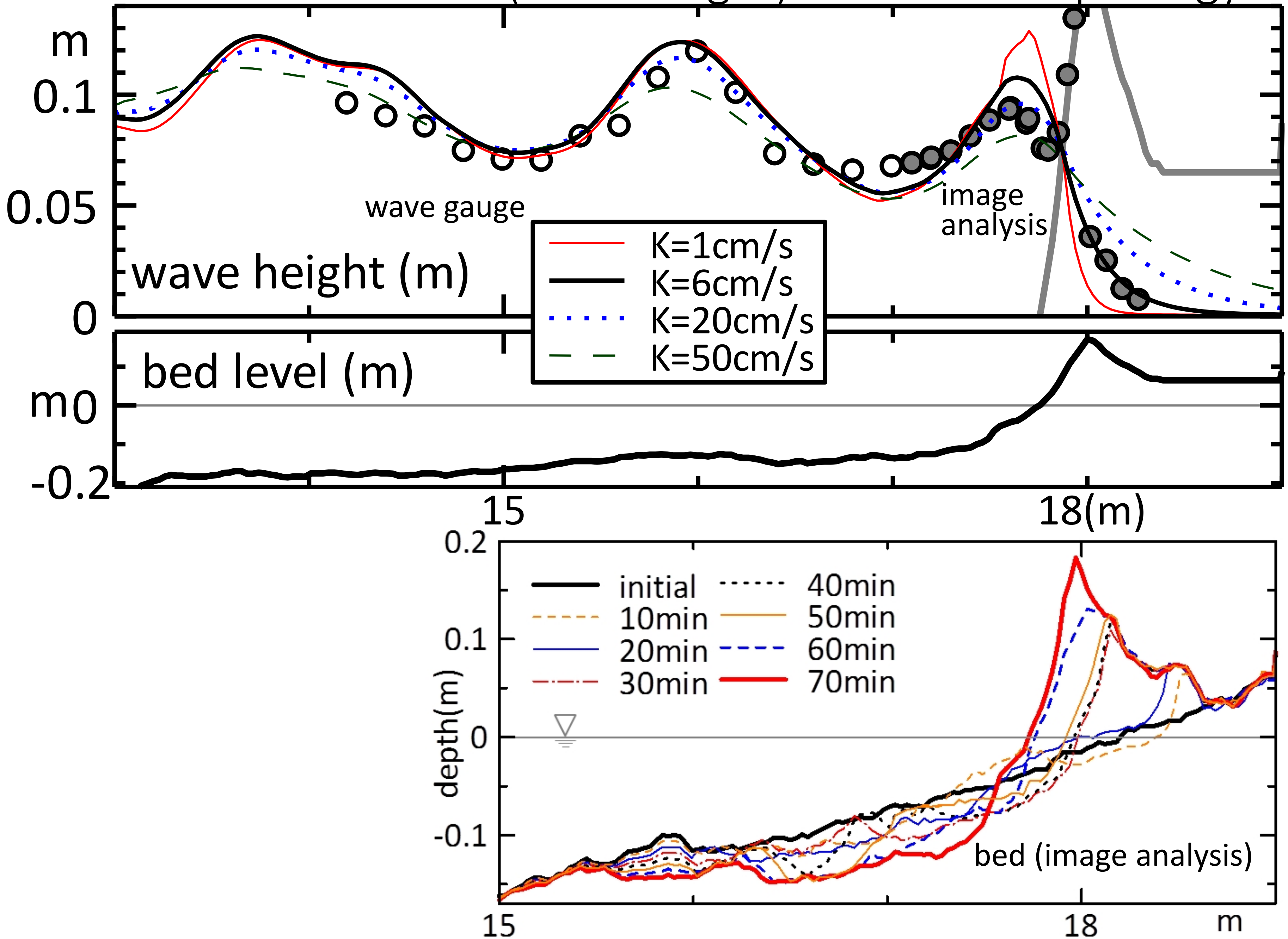
	Case1				Case2					Case3	
	1	2	3	4	1	2	3	4	5	1	2
wave height (cm)	13.08	13.94	12.46	13.40	14.41	8.54	7.51	7.36	7.07	13.38	6.75
period(s)	4	3	2	5	5	5	4	3	2	3	3

Image Analysis

(a)rectified image
(b)water was highlighted in monochromatic image with Z=B-1.2(R+G)
(c,d) time-change of the vertical lines at different cross-shore locations.
=> extract time-varying water level change



Extracted water level(wave height) and bed morphology



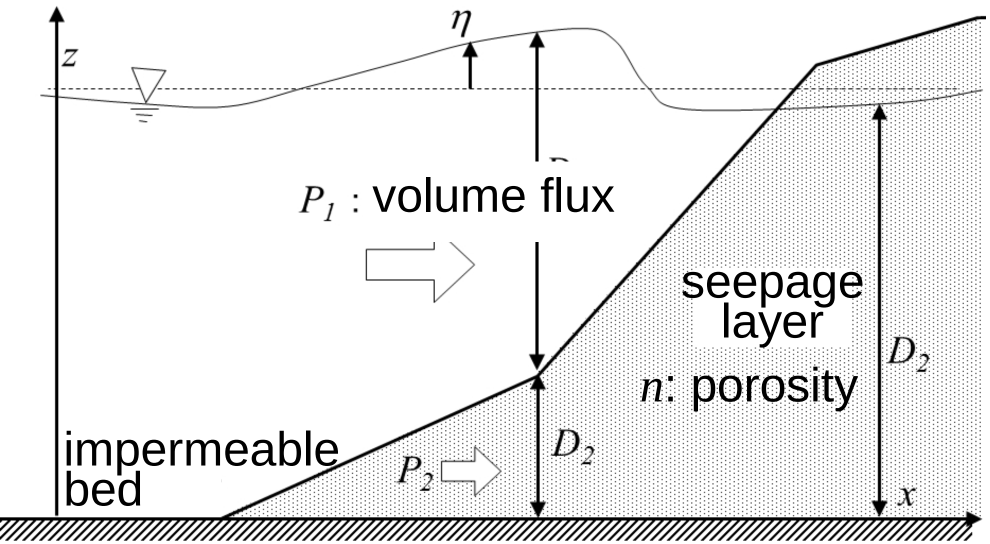
2. Modeling of transport on the sloping coral bed

- Wave-induced transport is dominant.
- Wave penetration on the coral bed.
- Bedload transport is dominant
- Steeply sloping coral bed induce wave reflection

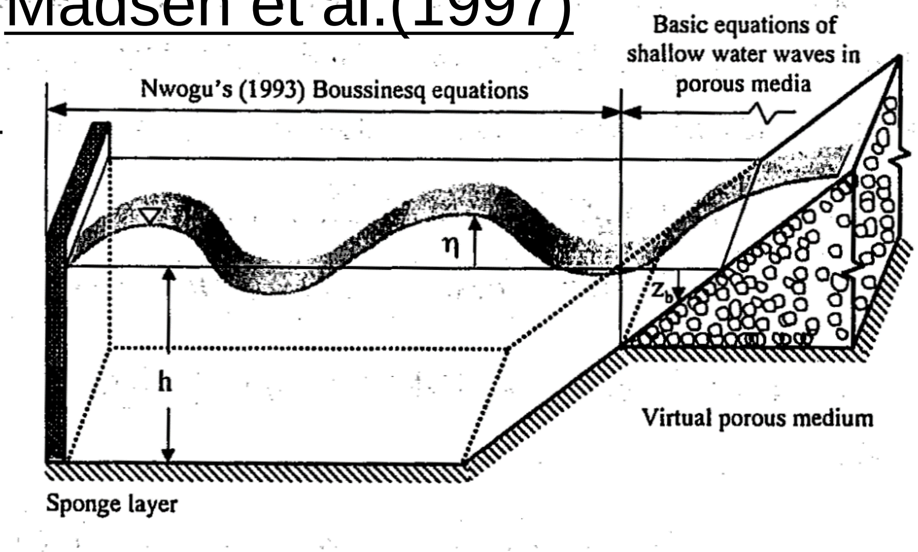
(A) Wave model: phase-resolved non-linear dispersive wave model accounting for seepage layer

(B)Transport model: Process-based bedload sediment transport model accounting for bed slopes and asymmetric wave profiles

Wave Model



Madsen et al.(1997)



$$\varepsilon \frac{\partial \eta}{\partial t} = -\frac{\partial P_1}{\partial x} - -\frac{\partial P_2}{\partial x} \qquad \varepsilon = \begin{cases} 1 \ (\eta > z_l) \\ n(\eta < z_l) \end{cases}$$

$$\frac{\partial P_1}{\partial t} + \frac{\partial}{\partial x}\left(\frac{P_1^2}{D_1}\right) + gD_1 \frac{\partial \eta}{\partial x} + \Psi + D_f + D_B = 0 \qquad \frac{\partial P_2}{\partial t} + gD_2 \frac{\partial \eta}{\partial x} + \frac{ng}{k} P_2 = 0$$

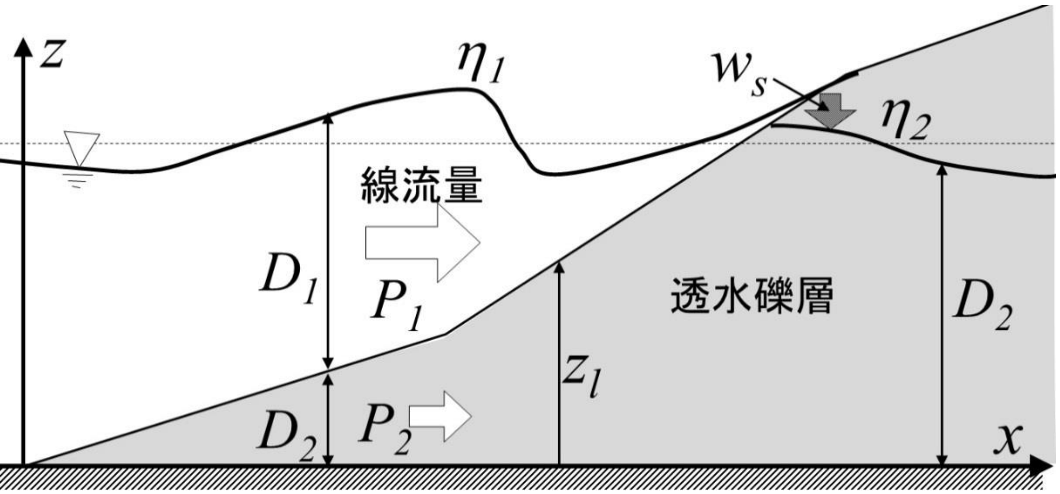
- Momentum equations were applied in two separate layers
- Dispersion-type broken wave dissipation model (Tajima et al., 2006)
- Breaking criteria is determined by the vertical pressure gradient(Hirayama&Hiraishi, 2004)

Modeling at swash zone

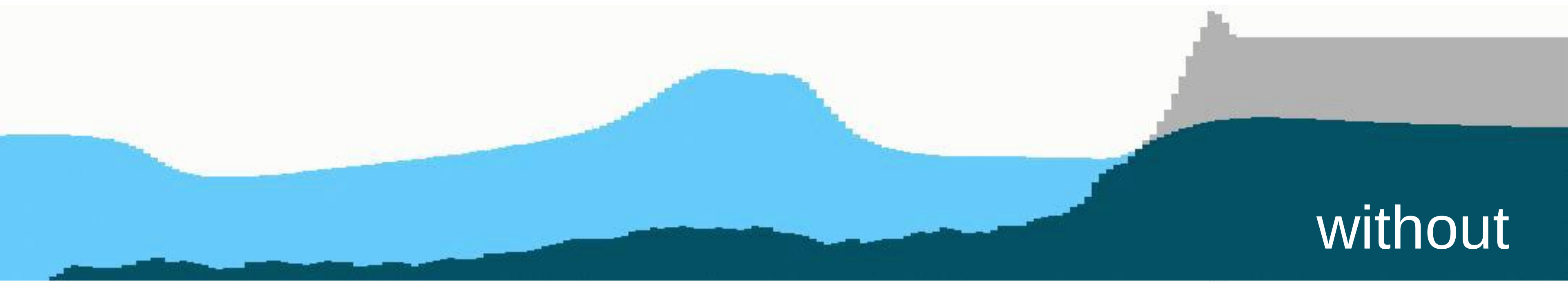
$$\eta_{1t} = -M_{1x} - W$$

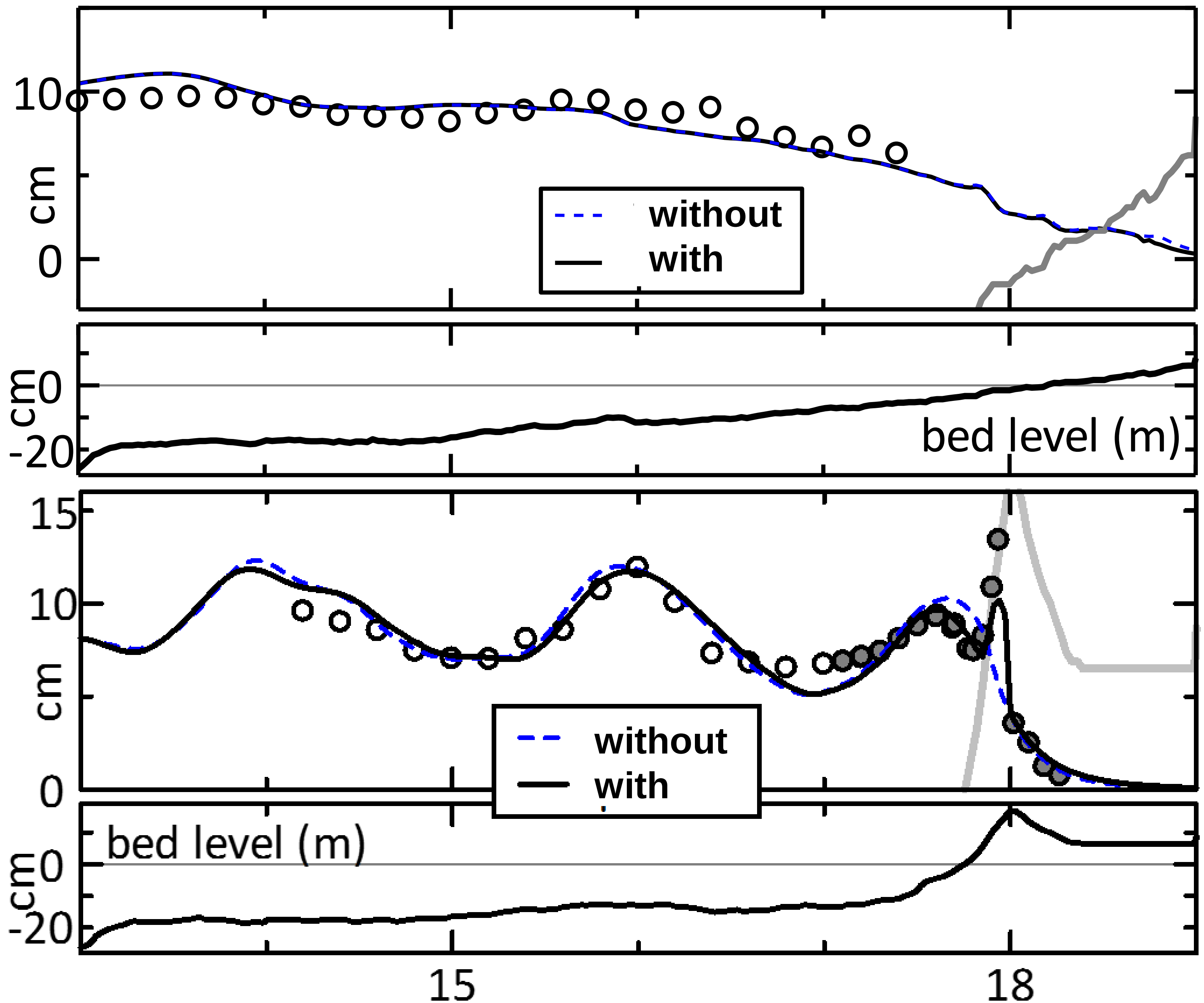
$$n\eta_{2t} = -M_{2x} + W$$

$$w_{st} = g - \frac{ng}{k} w_s$$



		M_1	M_2	W
$\eta_1 > z_l + \delta$	$\eta_2 > z_l - \delta$	$P_1 + P_2$	0	0
	$\eta_2 \le z_l - \delta$	P_1	P_2	nw_s
$\eta_1 \le z_l + \delta$		0	P_2	0





10
0
cm
without
with
0
-20
cm
bed level (m)
15
10
0
cm
without
with
bed level (m)
0
-20
cm
15
18

2. Modeling of transport on the sloping coral bed

- Wave-induced transport is dominant.
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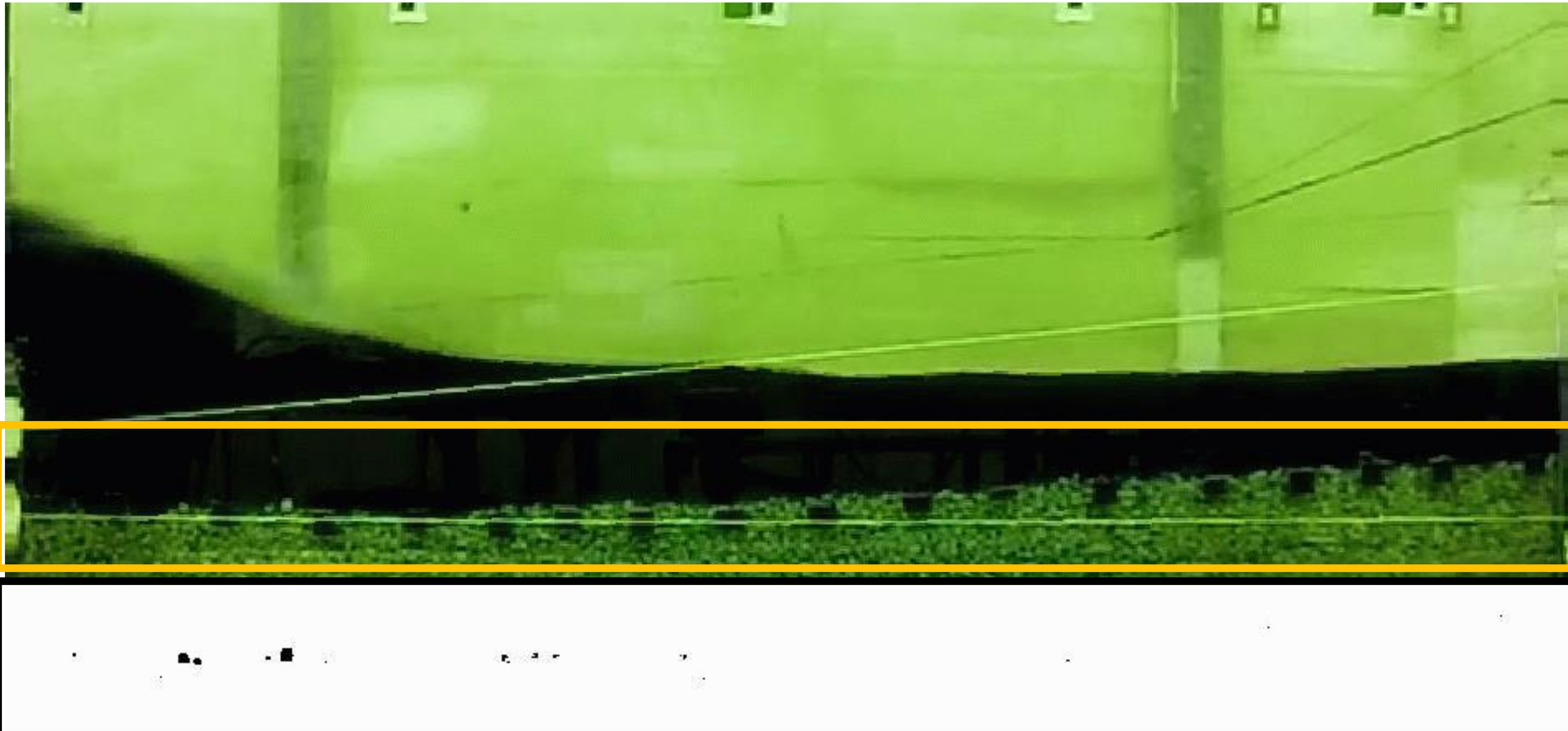
- Bedload transport is dominant
- Steeply sloping coral bed induce wave reflecti

(A) Wave model: phase-resolved non-linear dispersive wave model accounting for seepage layer

(B)Transport model: Process-based bedload sediment transport model accounting for bed slopes and asymmetric wave profiles

Behavior of coral gravels under the wave



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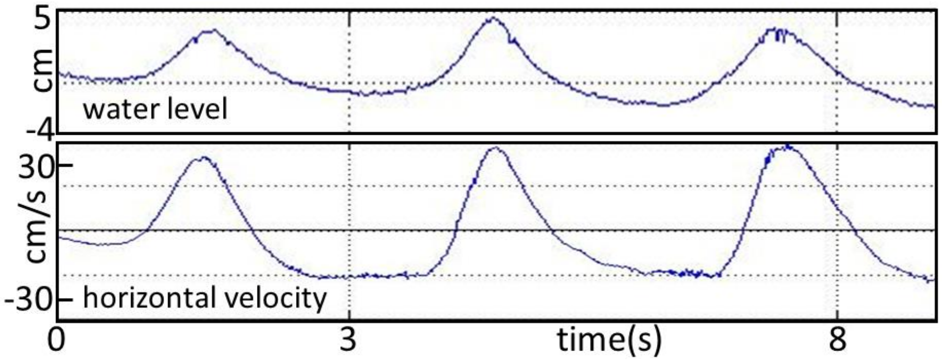
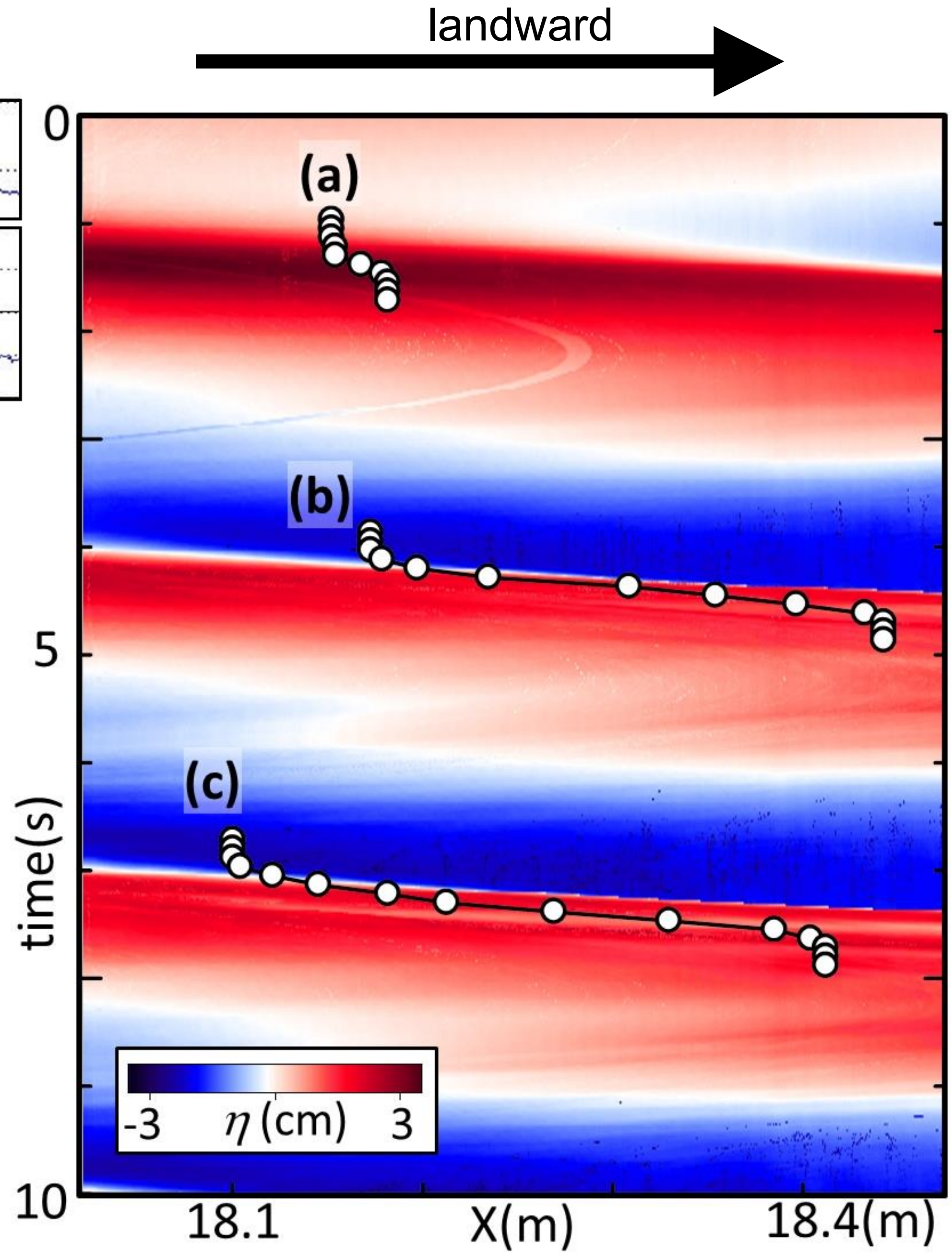
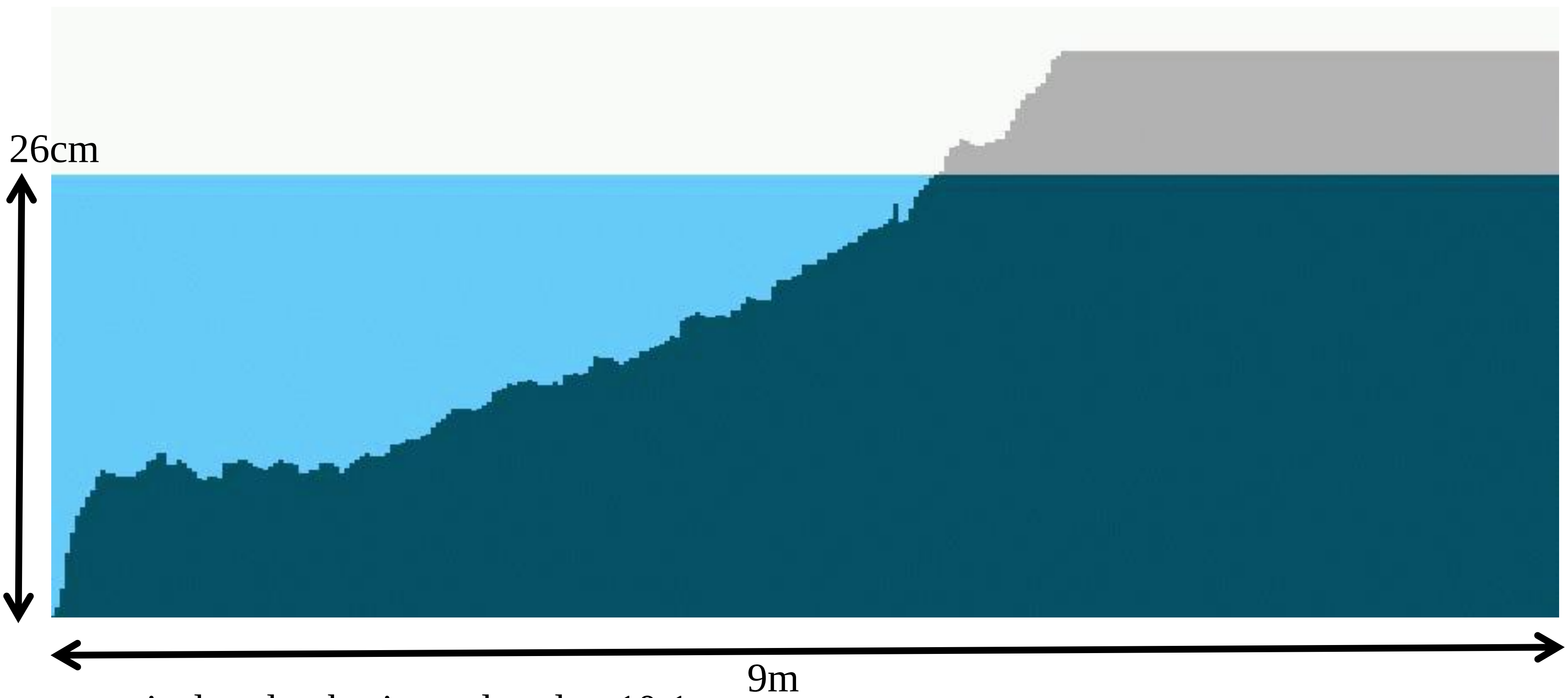


- Horizontal velocity corresponds to the water surface profiles.
- Gravels are initiated to move even when the water level is below the mean water level. >> acceleration is important?

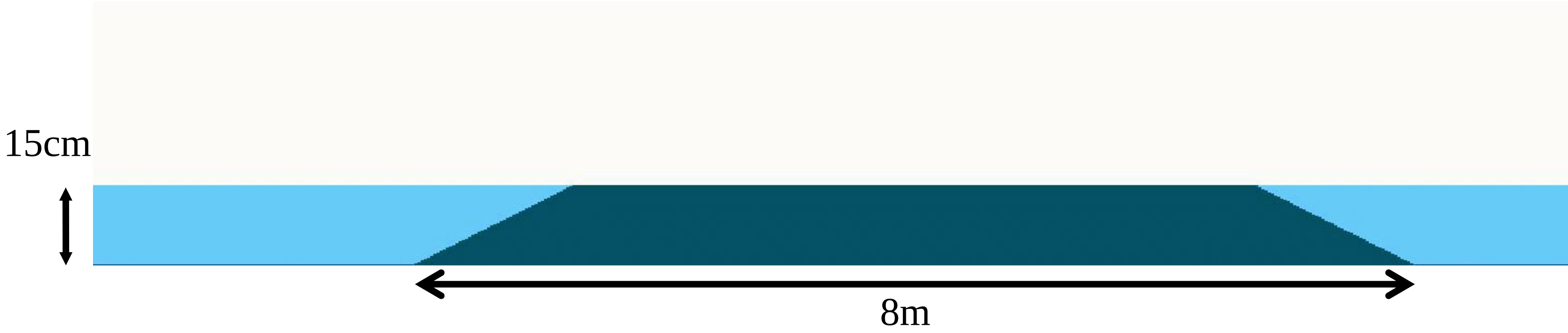


Morphology change



vertical scale : horizontal scale= 10:1

Cay formation affected by tide



- sufficient amount of gravels are needed to form a cay

Summary

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- Wave-induced transport has a dominant role to accumulate coral gravels around Ballast island.
- Both Hatoma island and deep holes on the reef appear to have significant influence on accumulation of coral gravels.