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SPH Modeling of Surf Zone Heating by Energy Dissipation of Breaking Waves

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Motivation: Does wave breaking warm up coastal waters?

- Breaking waves dissipate the incident wave energy.
- The law of energy conservation indicates that some of the dissipated wave energy would be transformed into heat.
- Can we measure or model the warm-up of coastal waters due to wave energy dissipation?

Wave breaking over a beach (Clark et al., 2011)

✓ Sinnett & Feddersen (2014) analyzed the surf zone heat budget and found that surf zone heating due to wave energy flux is important!

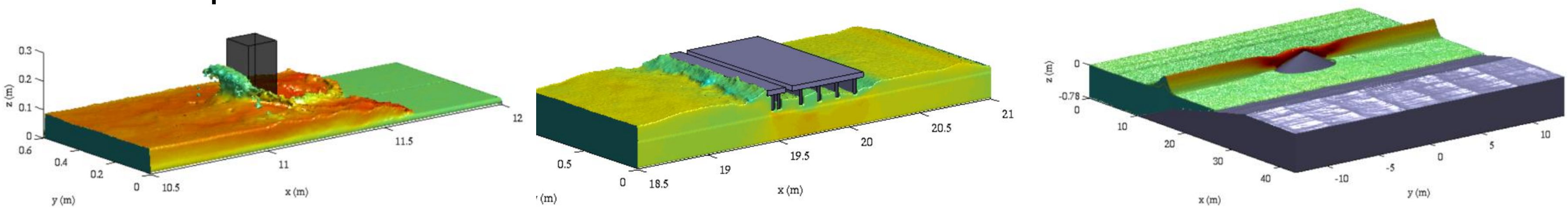
❖ This study investigates surf zone heating due to the energy dissipation of breaking waves by using the Smoothed Particle Hydrodynamics (SPH) method.

Sinnett & Feddersen, 2014. The surf zone heat budget: the effect of wave breaking. Geophysical Research Letters. 41, 7217-7226.

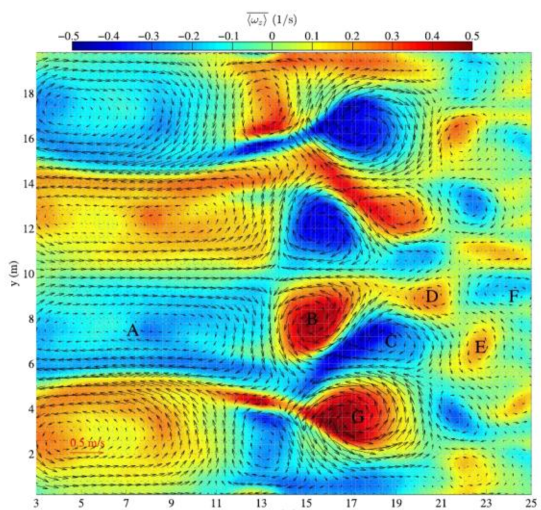
GPUSPH modeling of coastal processes

GPUSPH is an open-source implementation of the weakly compressible SPH method on GPUs (www.gpusph.org) [GPUSPH v4.1 was out!].

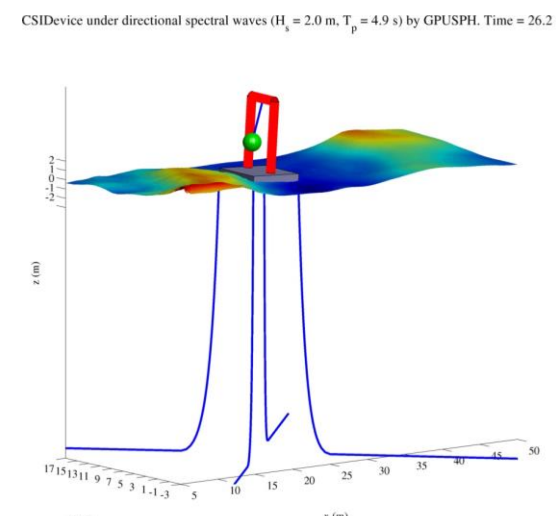
- A few examples …



Tsunami-structure interaction (Wei et al., 2015, 2016; Wei & Dalrymple, 2016)



Nearshore circulation (Wei et al., 2017)



Wave energy converters (Wei et al., in preparation)

What do you mean by "surf zone heating"?

- "Surf zone heating" means the increase in water temperature in the surf zone.

- Do you compute the increase/generation of temperature?
  - ❖ No, this study does not solve the temperature as unknown directly, but rather we examine the increase of internal energy in the water body. Why?
  - ❖ To ensure the conservation of energy

- The first law of thermodynamics: $\Delta U = Q - W$
  where ΔU is the change of internal energy; *Q* is the heat; *W* is the work

- This study considers a "thermally isolated system", which does not exchange mass flow and heat energy. As a result, the increase of internal energy in the wave basin is solely due to the incident wave energy offshore.

Governing equations

- Mass & momentum conservation of weakly compressible SPH (e.g., Dalrymple & Rogers, 2006)

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho\nabla\cdot\mathbf{u}$$

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{\nabla P}{\rho} + \mathbf{g} + \nu_0\nabla^2\mathbf{u} + \frac{1}{\rho}\nabla\cdot\tau$$

$$P = \beta\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right]$$

- Internal energy (*U*) (Fulk, 1994)

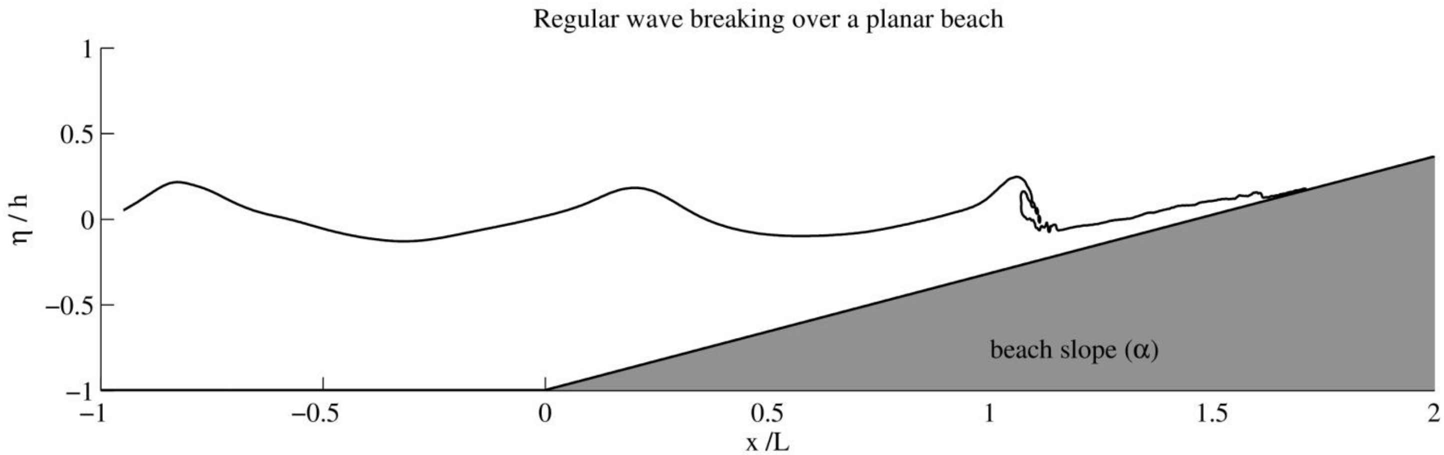
$$\frac{\mathrm{D}U}{\mathrm{D}t} = -\frac{1}{2}m\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t}\cdot\mathbf{u}$$

- "*Equivalent*" Temperature (*T*)

$$T = \frac{U}{c_p\cdot m}$$

where t is the time; ρ is the fluid density; $\mathbf{u}$ is the particle velocity; P is the pressure; U is the particle internal energy (unit: J); m is the particle mass; $\mathbf{g}$ is the gravitational acceleration; ν_0 is the laminar kinematic viscosity; and τ is the turbulence stress tensor; and c_p is the specific heat capacity (unit: J/(Kg Kelvin)).

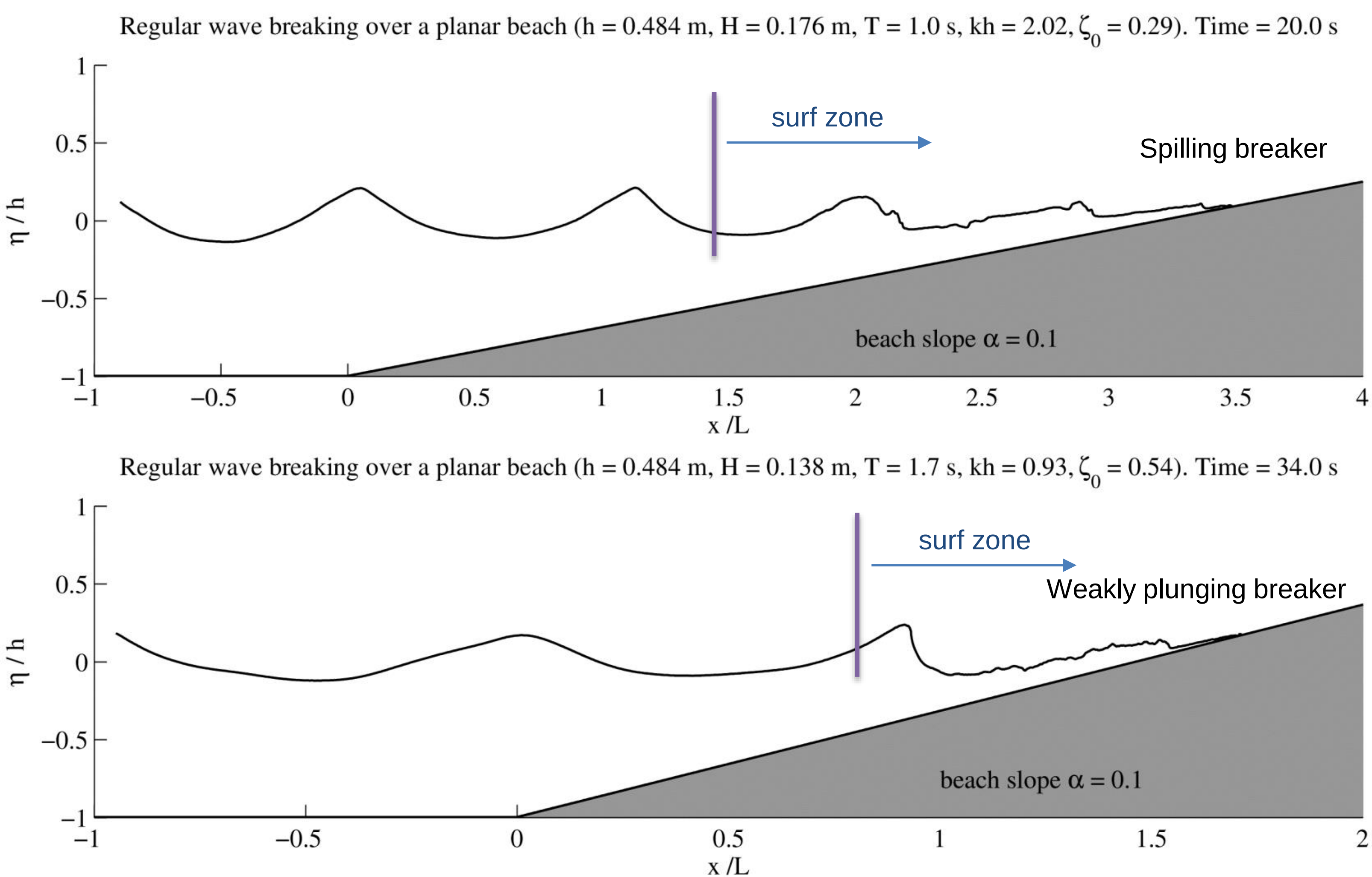
Numerical experiments



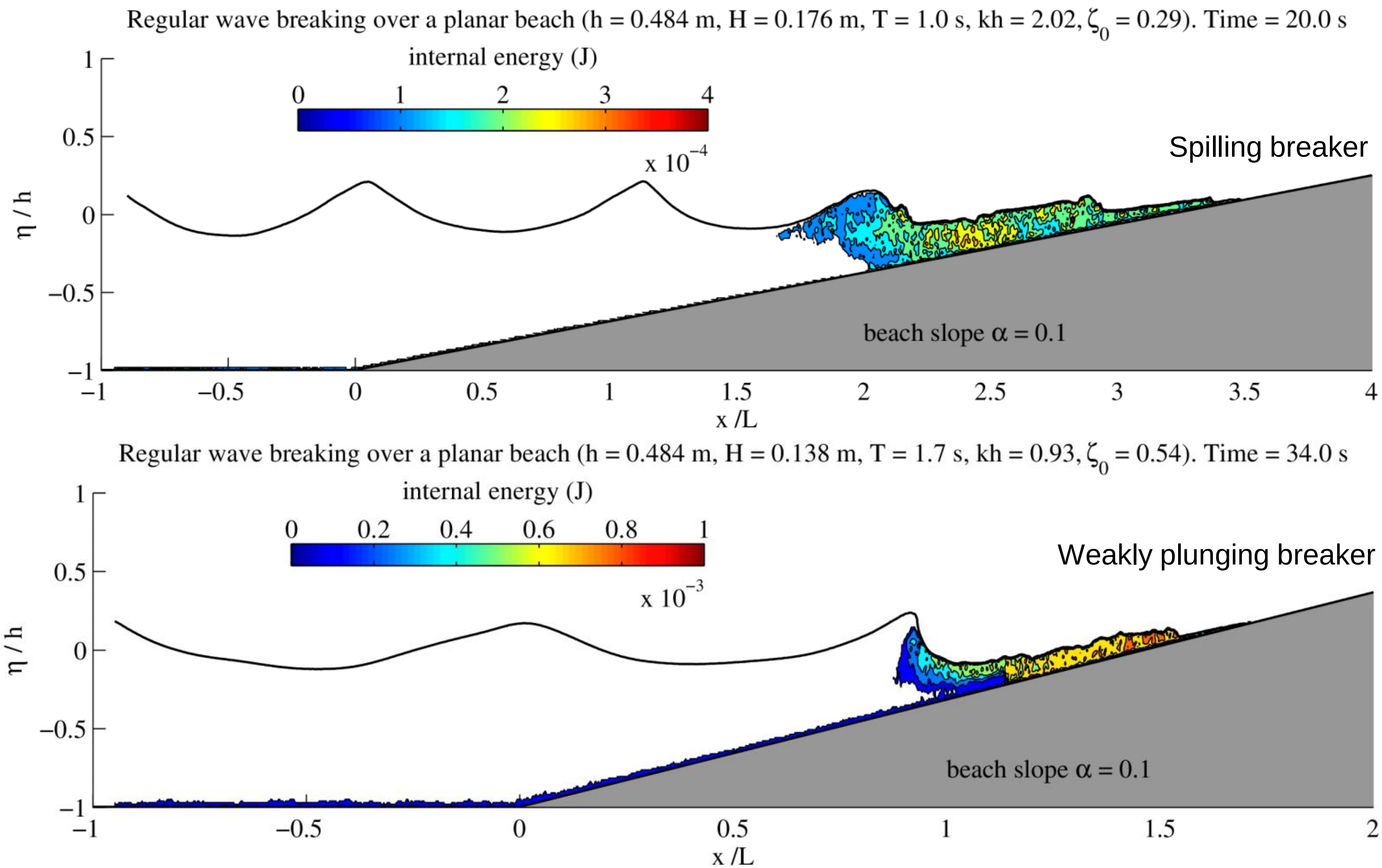
Index	h (m)	H (m)	T (s)	L (m)	kh	ζ_0	
1	0.484	0.176	1.0	1.51	2.02	0.29	spilling breaker
2	0.484	0.138	1.7	3.30	0.93	0.54	weakly plunging breaker

- 2D (or long-crested) waves.
- The planar beach slope is 0.1.
- The numerical wavemaker is placed at one wave length away from the beach toe.
- Both spilling breaker and weakly plunging breaker are considered based on the surf similarity parameter ($\zeta_0 = \frac{\tan\alpha}{\sqrt{H_0 L_0}}$) of Battjes (1975).

Long-crested waves breaking over a beach



Surf zone heating



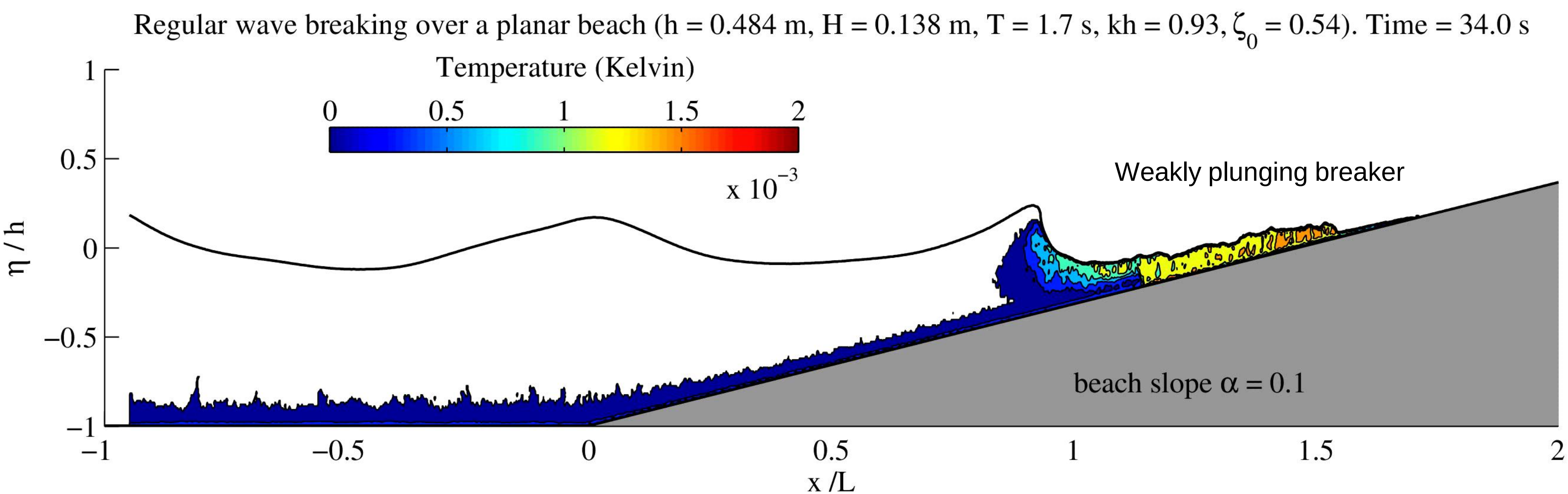
- (1) Internal energy generation mainly in the surf zone; (2) internal energy increases over time; (3) beach heating due to intermediate-depth waves & dissipative numerical beach (zero velocity at wall boundary)

Surf zone heating (Temperature)

- Temperature (T) can be estimated from internal energy (U) by

$$T = \frac{U}{c_p \cdot m}$$

where m is the particle mass, and c_p is the specific heat capacity.



Surf zone energy budget

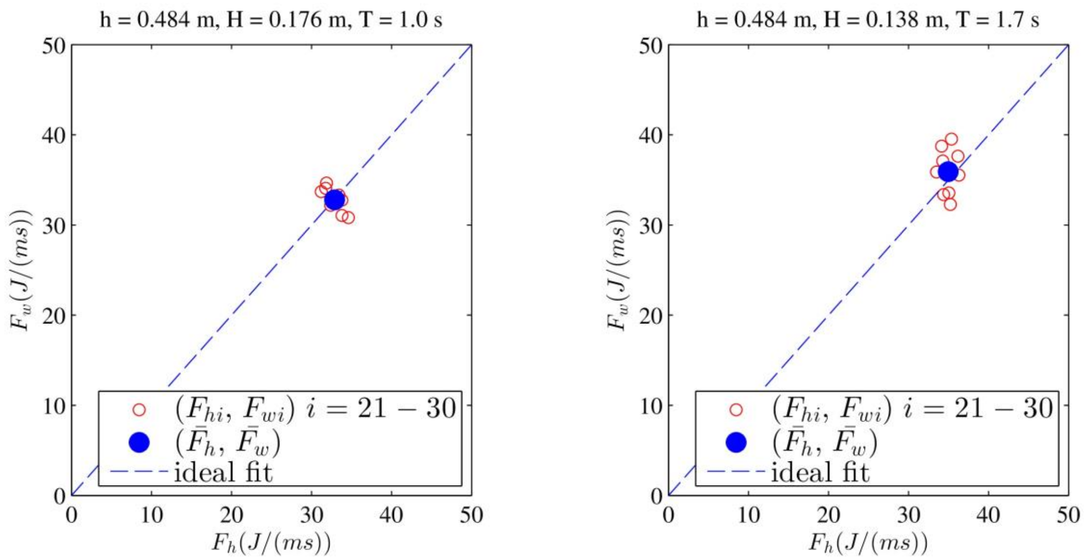
- Incident wave energy flux per unit width: $F_w = EC_g = \frac{1}{8}\rho g H^2 C_g$

where $E = \frac{1}{8}\rho g H^2$, $C_g = nC = \frac{1}{2}\left(1 + \frac{2kh}{\sinh 2kh}\right)C$

- Internal energy increase rate per unit width: $F_h = \frac{1}{L_y}\frac{\mathrm{D}U_s}{\mathrm{D}t}$

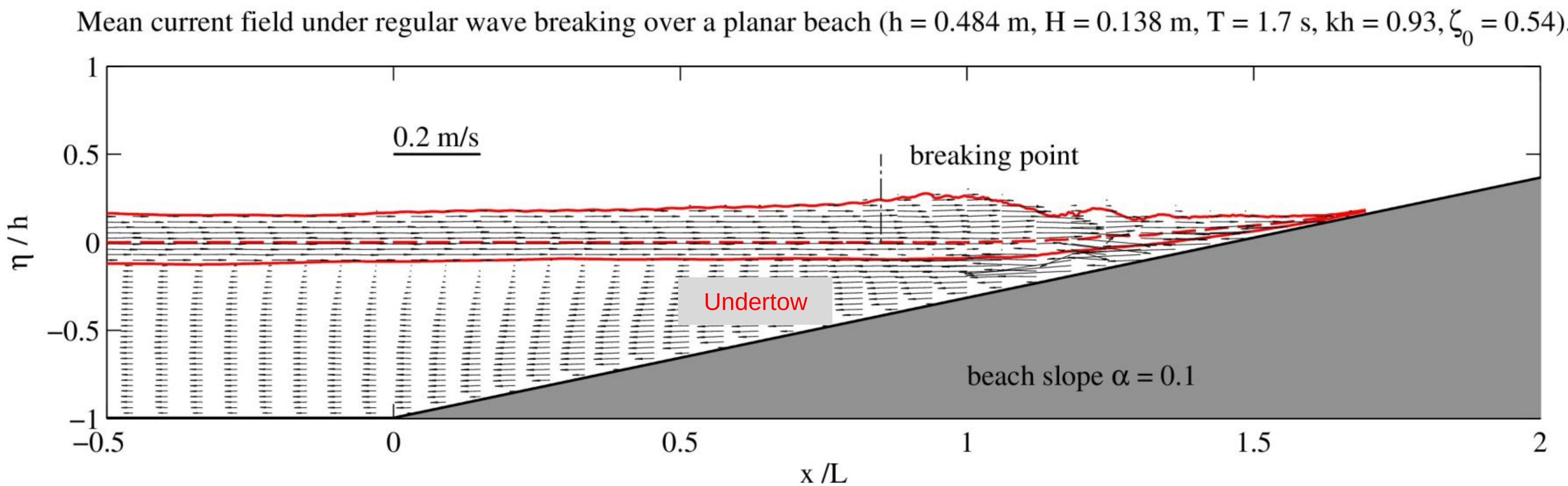
where L_y is the basin width, $U_s = \sum_{i=1}^{N_p} U_i$

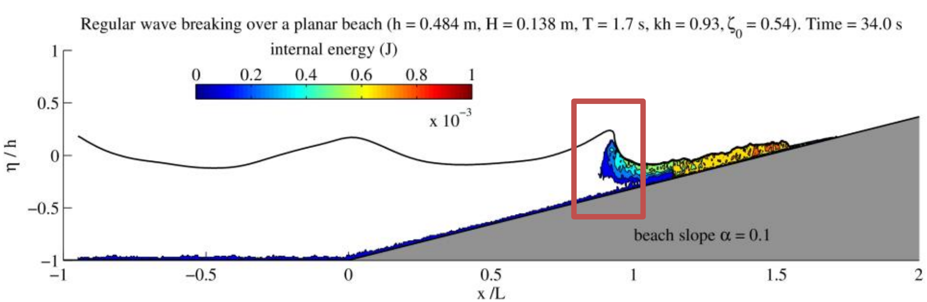
- Energy budget was estimated by averaging 10 waves (i.e., from 20T to 30T) when surf zone process is relatively stable.



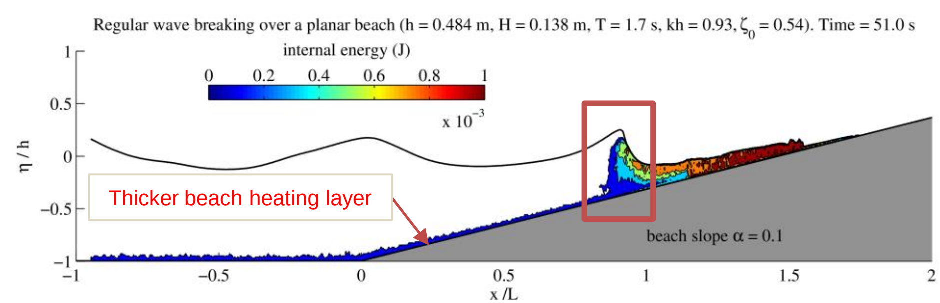
- The incident wave energy is fully converted into internal energy of the system.

Undertow: the carrier of heat offshore





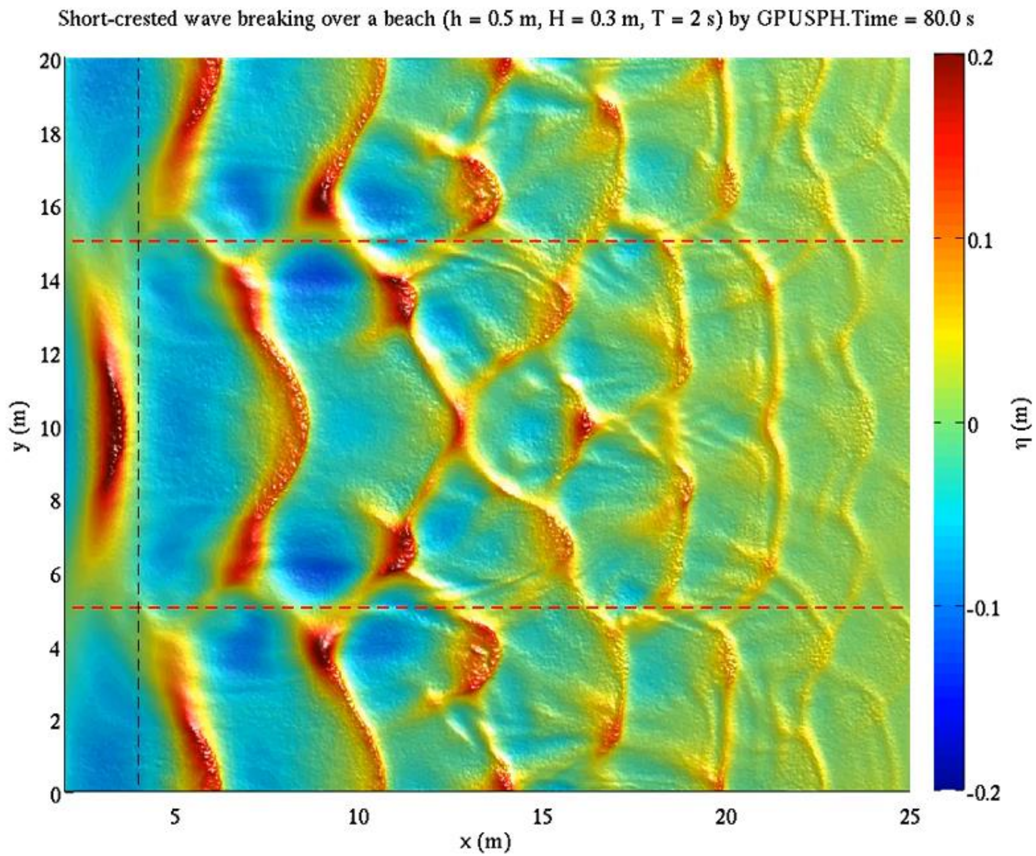
Internal energy distribution at t = 20T



Internal energy distribution at t = 30T

- Undertow transports internal energy offshore and (partially) contributes to the increase of internal energy near the basin bottom.

Short-crested waves in the surf zone

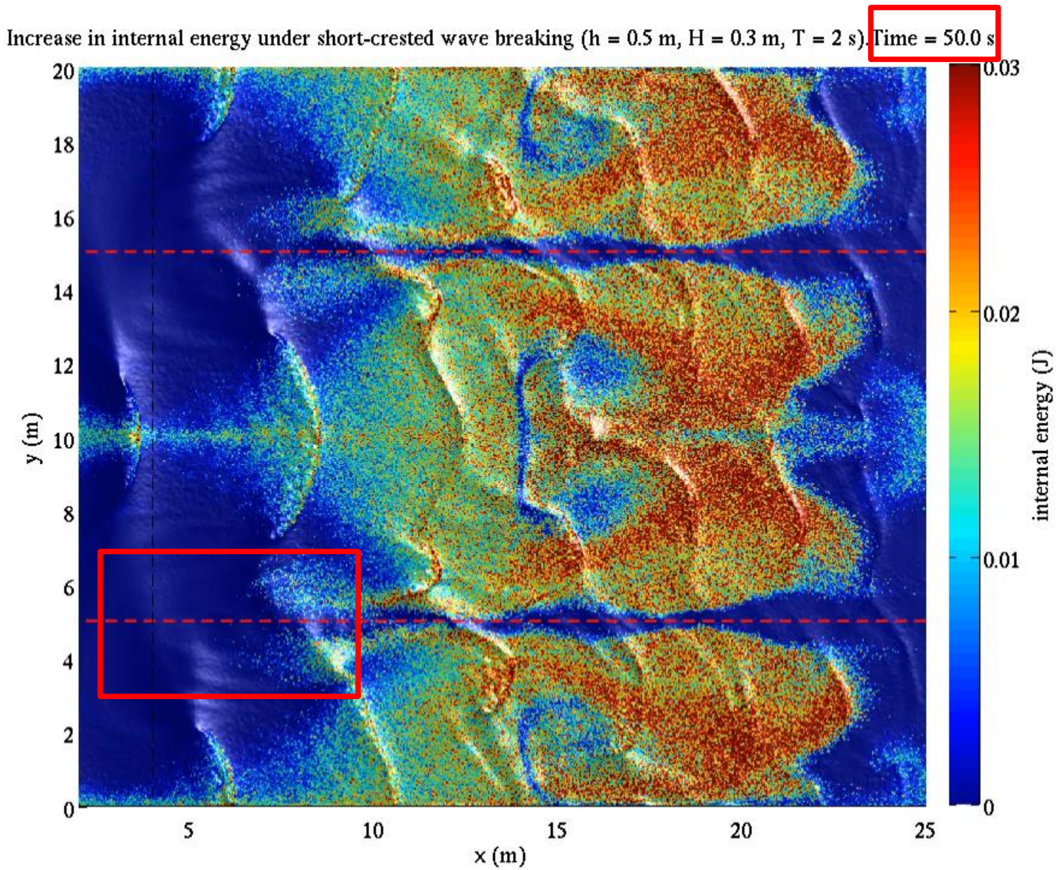


We generated short-crested waves by intersecting wave trains, and we observed:

- Isolated breakers
- wave amplitude diffraction
- Wave-driven currents, e.g., undertows & rip currents
- Complicated nearshore circulation pattern
- …

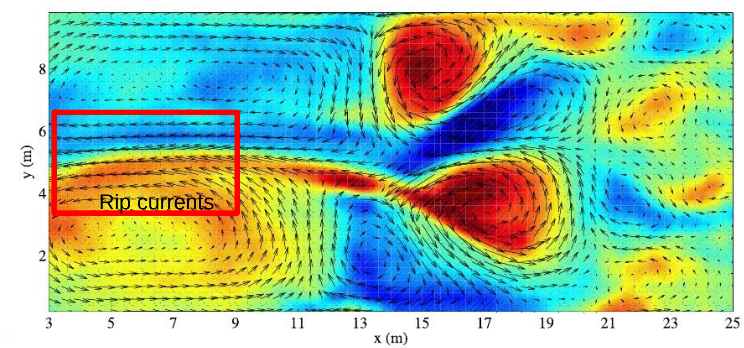
Wei, et al., 2017. Short-crested waves in the surf zone. JGR: Oceans. https://doi.org/10.1002/2016JC012485.

Surf zone heating driven by short-crested wave breaking



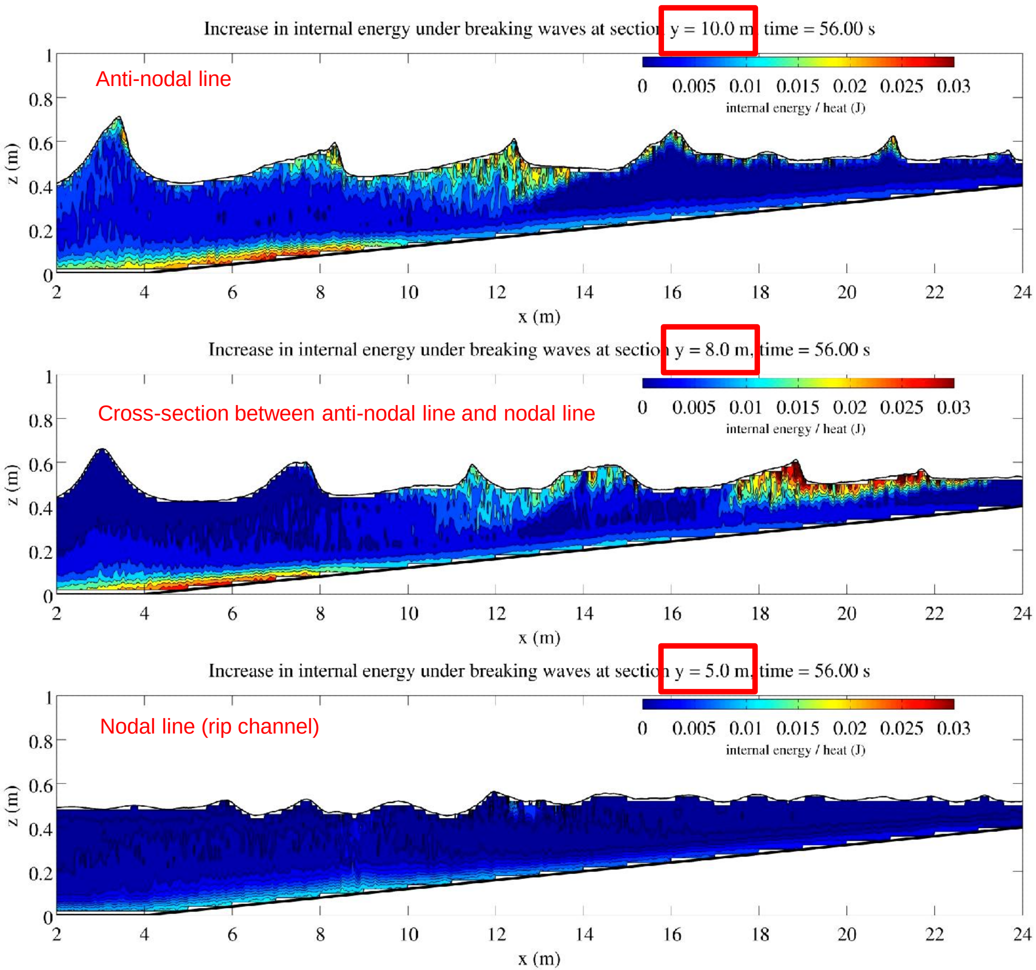
Internal energy profile at the free surface from 25T to 35T.

- Internal energy generation in the breaking region; it mainly follows the trajectory of isolated breakers
- Internal energy increases over time
- Wave-driven currents transport internal energy, in particular, internal energy is transported offshore near the rip channel
- …



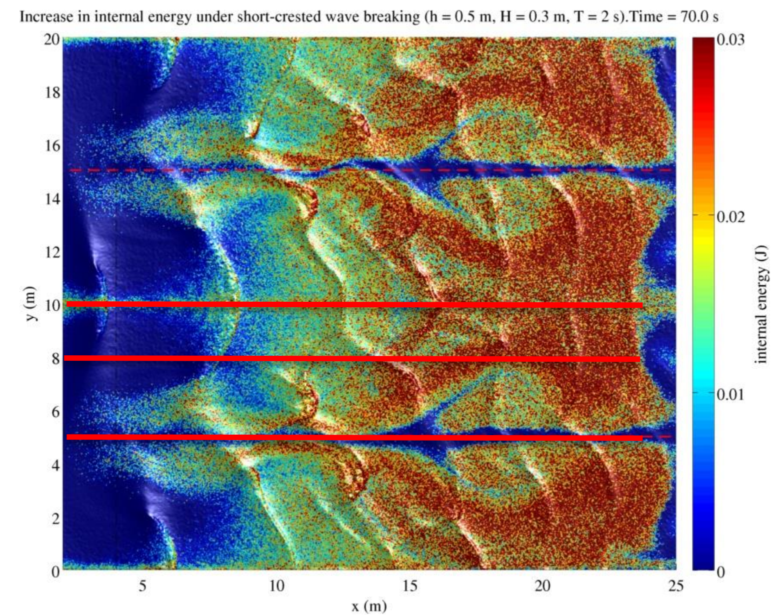
Time- and depth-averaged current field colored by mean vertical vorticity (Fig. 8 (b) of Wei et al., 2017).

3D distribution of water heating under waves



Cross-section view of internal energy generation under breaking waves

- y = 10 m: energetic wave breaking, internal energy generation near the upper water column
- y = 8 m: internal energy generation and energy advection alongshore
- y = 5 m: almost no internal energy generation near the rip channel



Summary

- Breaking of water waves in the surf zone generates heat (or increases the internal energy of the water body)
- The dissipated incident wave energy is fully converted into the internal energy in a closed system as used in the present study
- Wave-driven currents (e.g., undertows and rip currents) transport the generated heat from the surf zone to offshore area

Thank you for your attentions!

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