Laboratory observations of dissolved carbon dioxide transport under regular breaking waves

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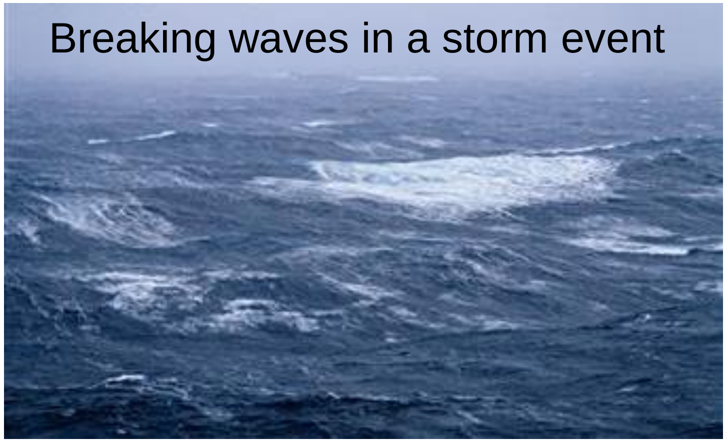
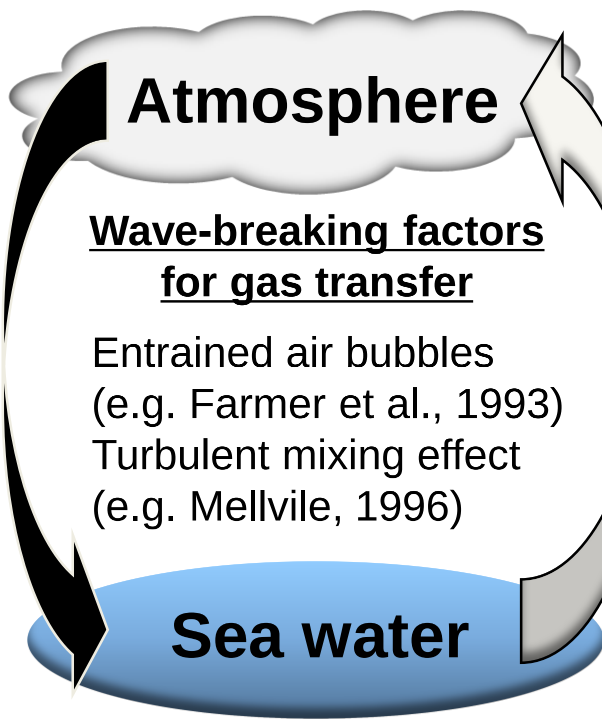
Introduction

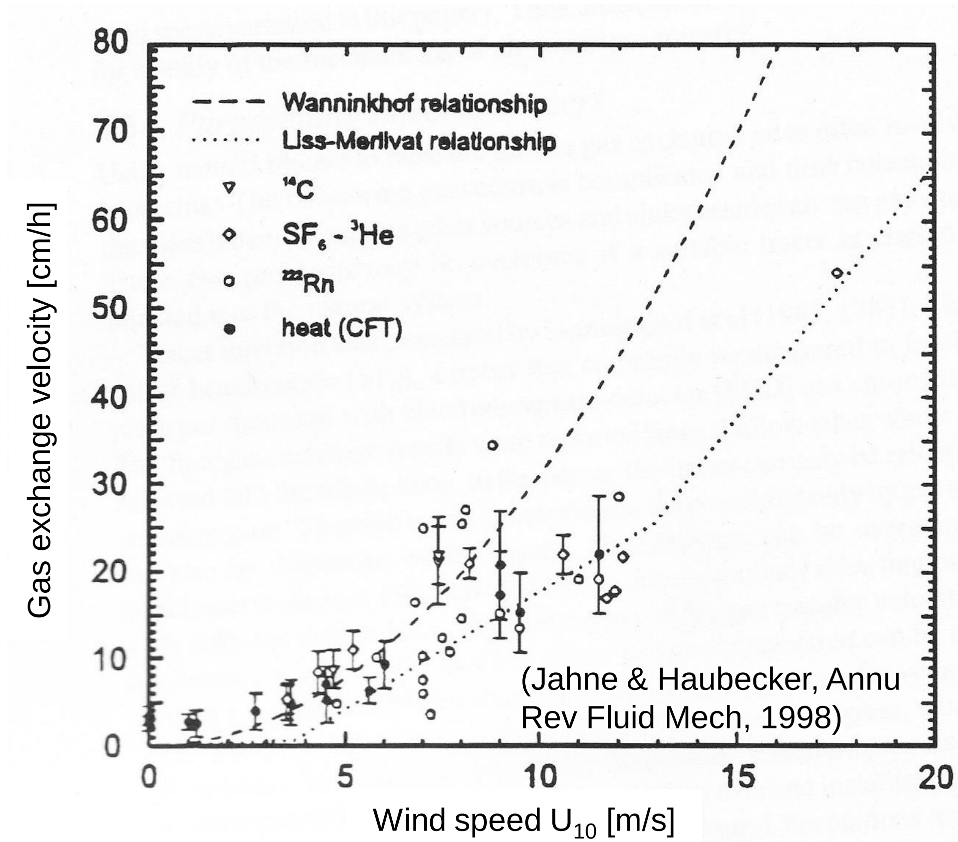
Air-sea gas exchange over the ocean



<u>Conventional gas exchange models</u>

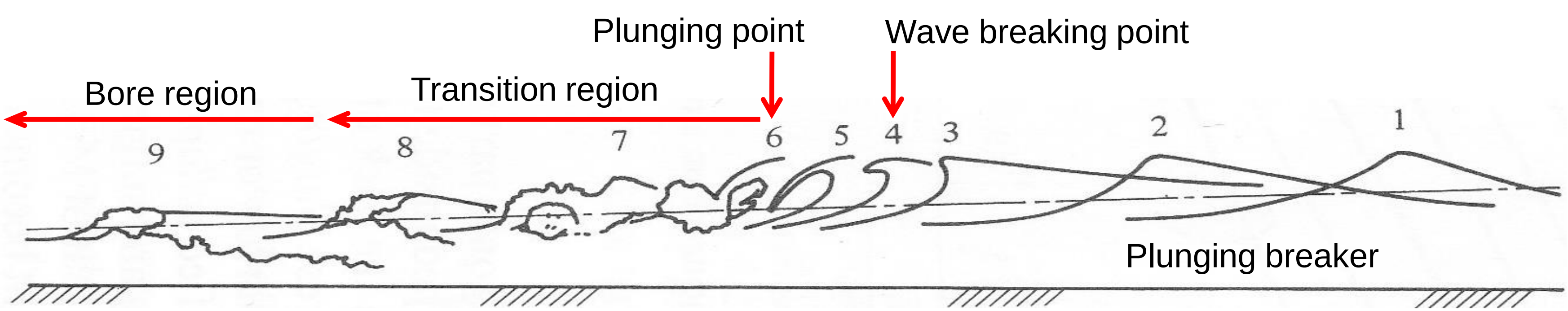
Simple model parameterized only by wind speed U_{10}
(e.g., Liss & Merlivat, 1986).





Introduction

Air-water turbulent flows in a surf zone



(R. G. Dean & R. A. Dalrymple, World Scientific)

Fully developed turbulent bore ⇐ Strong turbulence

Small number of air bubbles ⇐ Large number of air bubbles

Dissolved gas concentration and gas transfer velocity vary as waves propagate in a surf zone.

Introduction

Final goal of our study

- To model the gas transfer velocity in a surf zone.

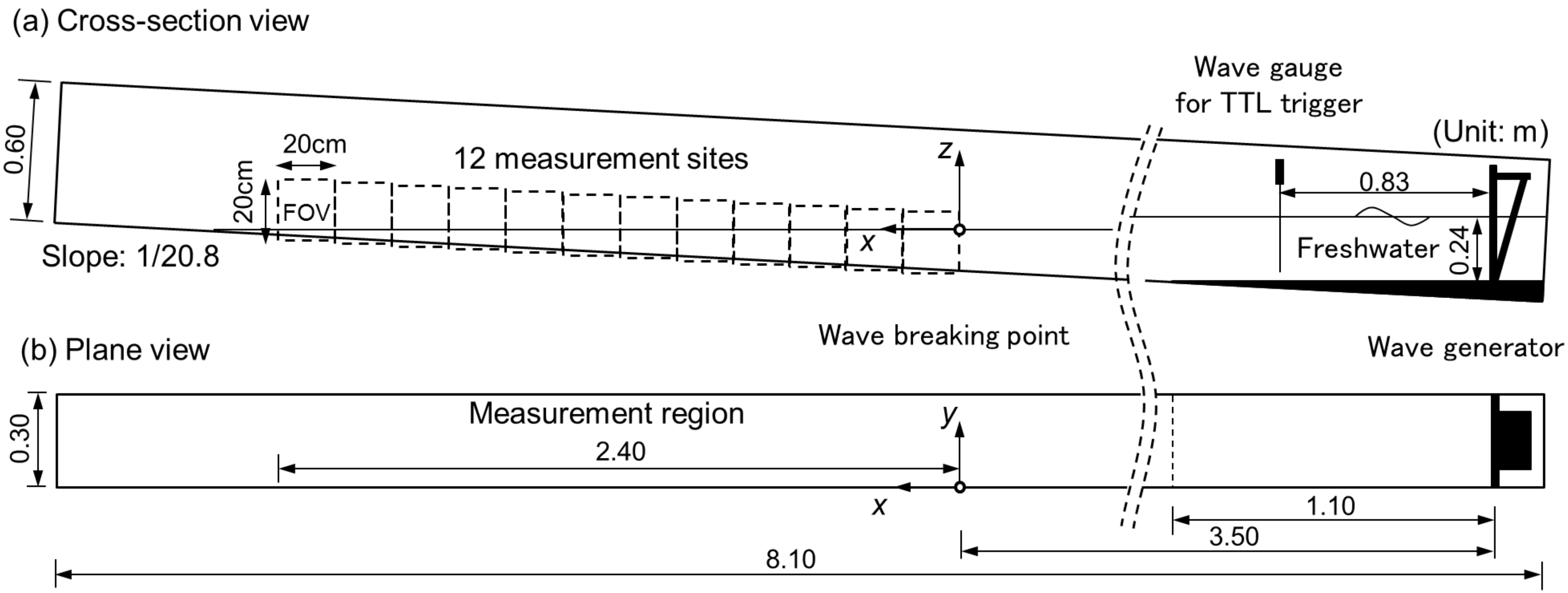
Object of this study

- To elucidate the gas transfer process in a surf zone.

Methodology

- Concentration field of dissolved carbon dioxide (DCO_2), velocity field and entrained bubbles were experimentally measured in a wave flume.
  - DCO2 concentration field: Laser induced fluorescence (LIF)
  - Velocity filed: Particle image velocimetry (PIV)
  - Entrained bubbles: LED backlight

Experimental setup and wave condition



- High speed video camera：8 bit, 250 fps
- Image resolution: 1,000 x 1,000 pixels (0.02 cm/pixel)
- Duration of image recording：21.8s

Case No.	Wave period T (s)	Breaking wave height H_b (cm)	Breaking wave deoth h_b (cm)	Bottom slope	Breaker type	Surf similarity parameter
Case1	1.5	13.0	13.9	1/20.8	Spilling/Plunging	0.247

LIF measurement for DCO_2 concentration field

Concentration field of dissolved carbon dioxide (DCO_2) was measured using LIF.

Fluorescent dye uranine was used in the LIF.

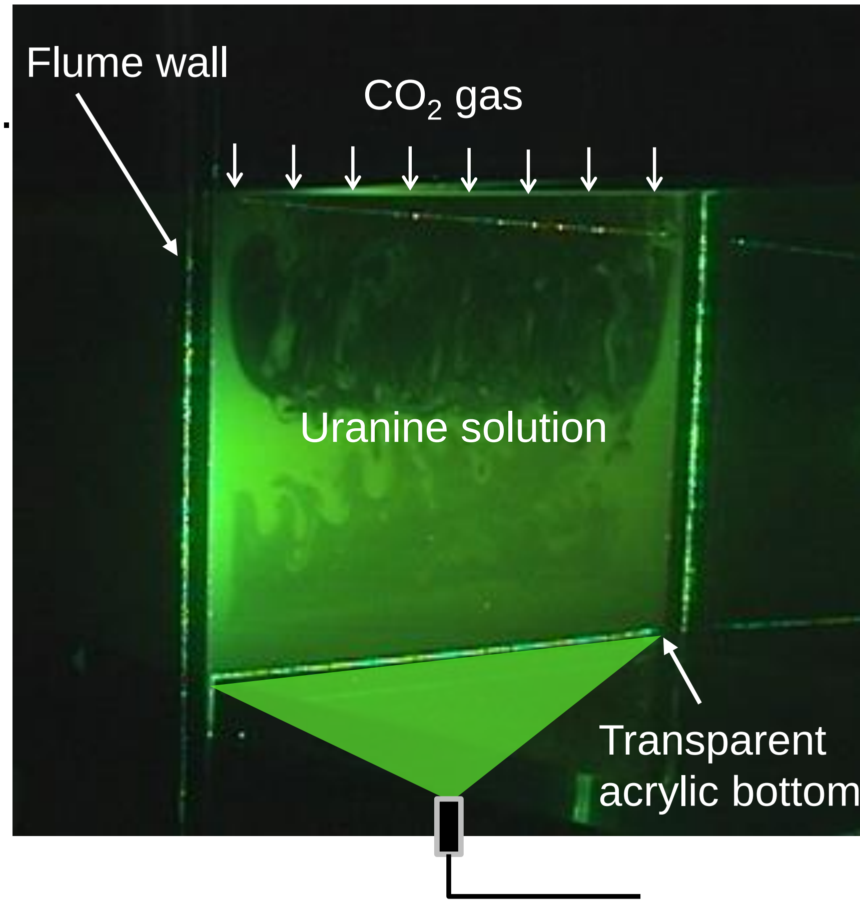
Fluorescence intensity of uranine is sensitive to pH in the range of pH4 to pH8.

CO_2 gas into water

pH decreases

Fluorescence intensity decreases

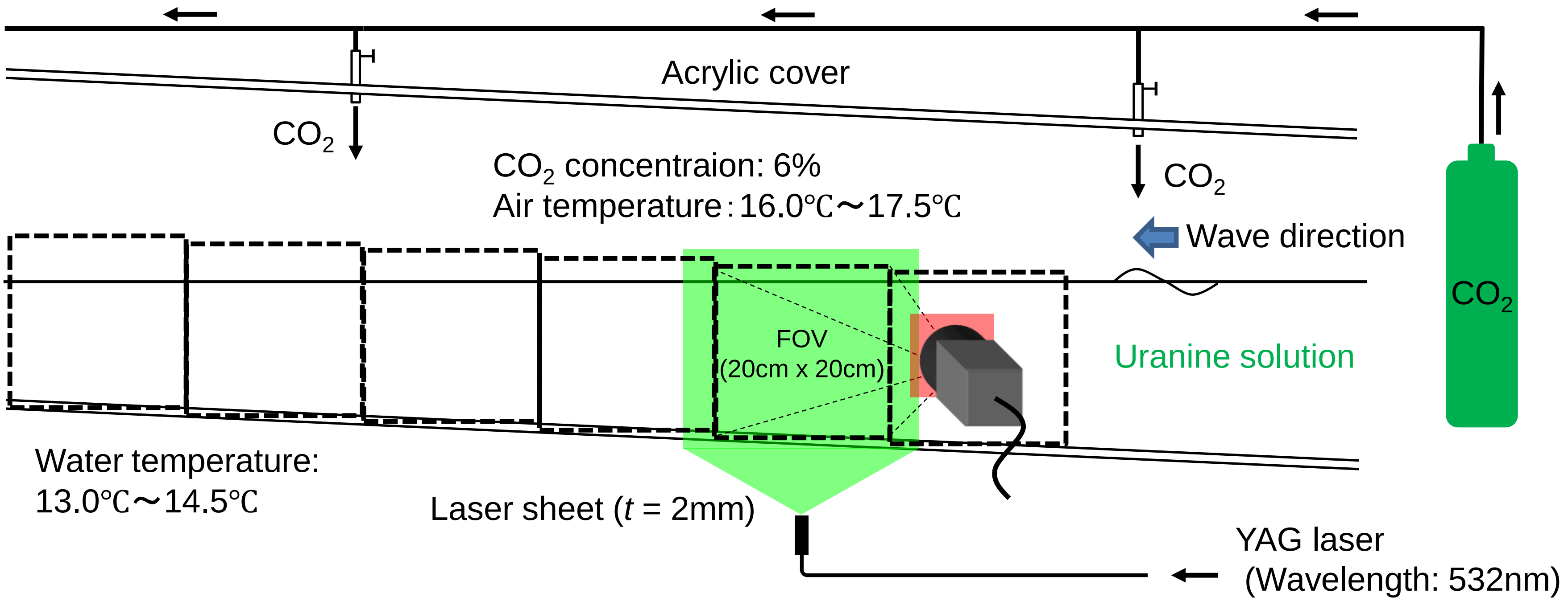
DCO_2 concentration was visualized by obtaining the relation between fluorescence intensity and DCO2 concentration.



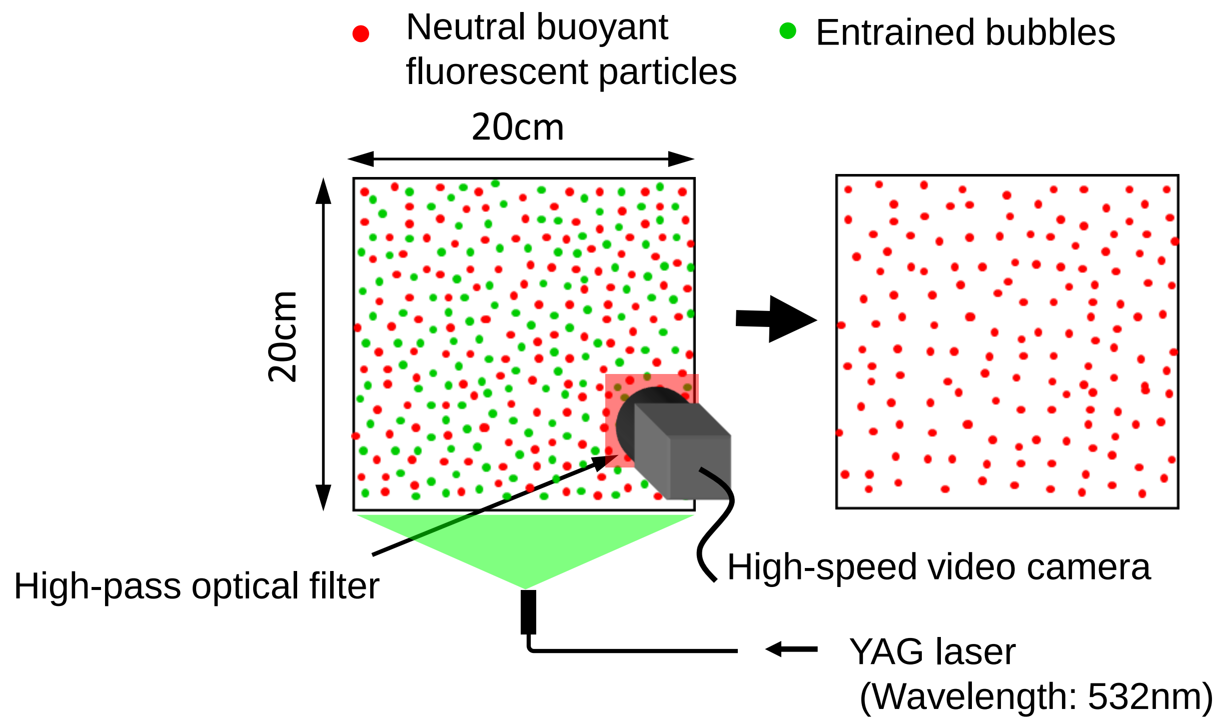
YAG laser sheet
(Wave length: 532 nm)

LIF measurement for DCO_2 concentration field

<Cross-section view>



PIV measurement for velocity field



- Sixteen trials were performed for each measurement site.
- Ensemble average was taken over the 16 trials to define the ensemble averaged velocity $\overline{u}$ *and* $\overline{v}$.

Turbulent energy k is defined as

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right) \qquad u' = u - \overline{u} \qquad v' = v - \overline{v}$$

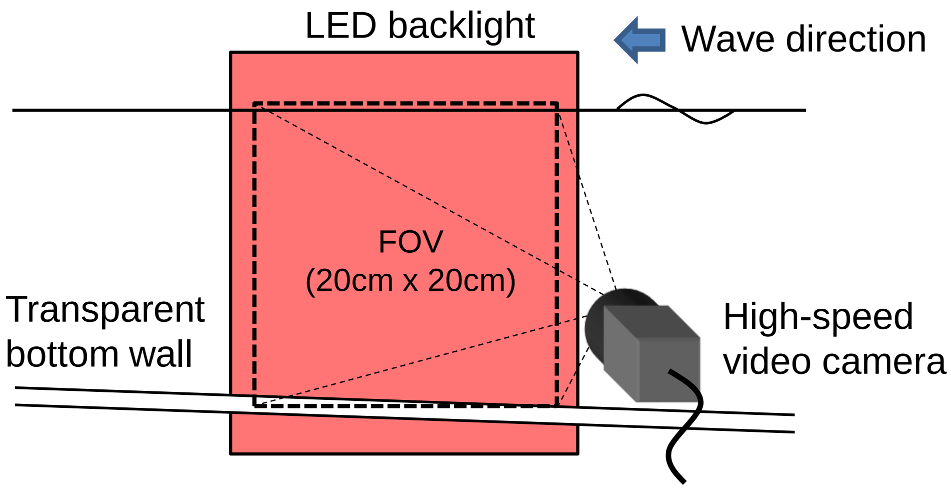
u: instantaneous horizontal velocity

v: instantaneous vertical velocity

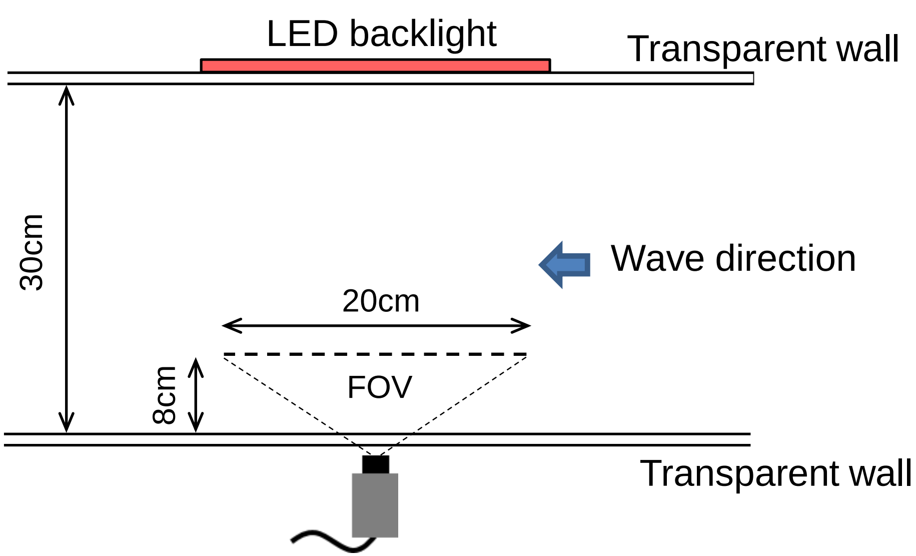
$\overline{}$: ensemble-averaging operation for instantaneous values

LED backlight for visualization of entrained bubbles

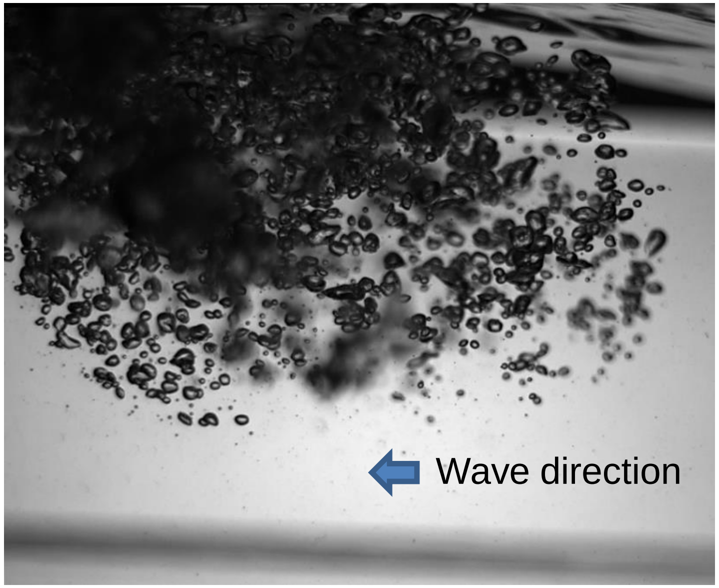
<Cross-section view>



<Plane view>



Visualized entrained bubbles

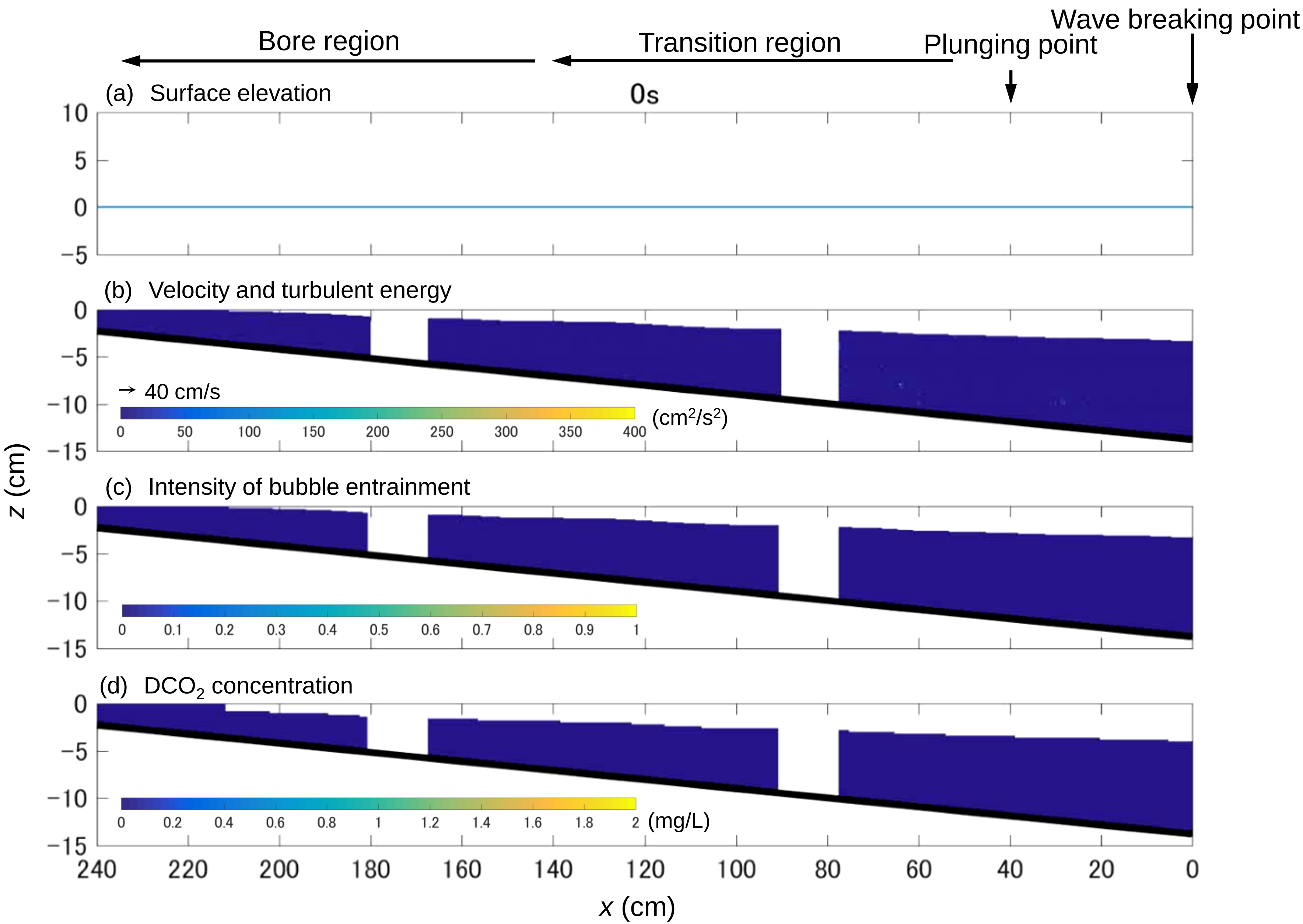


$$Intensity\ of\ bubble\ entrainment: = \frac{I_{ini} - I_{bub}}{I_{ini}}$$

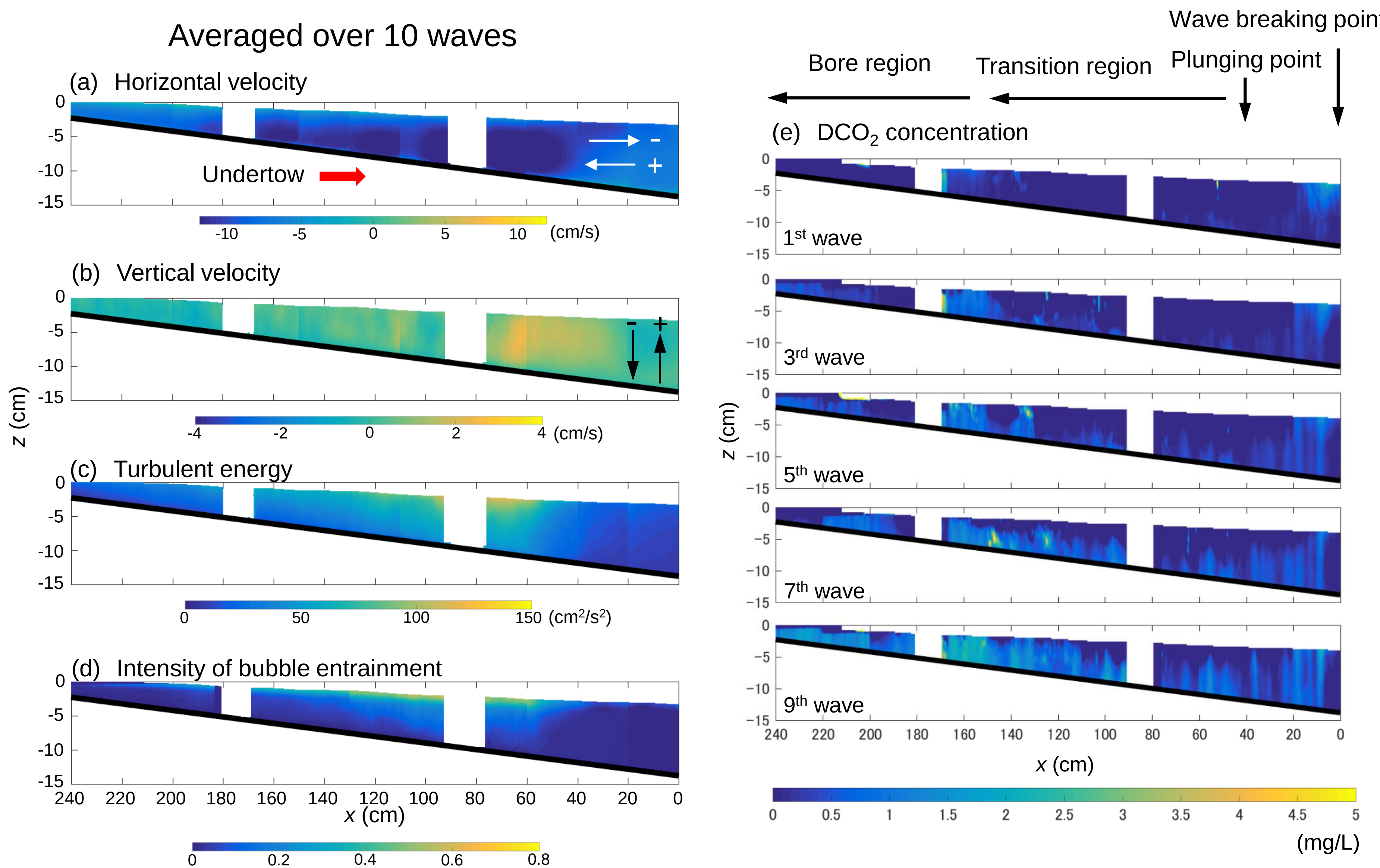
I_{ini}: *Non-aerated state image intensity*

I_{bub}: *Bubble image intensity*

Temporal variations in cross-shore distributions of surface elevation, velocity, turbulent energy, bubble image intensity and DCO_2 concentration



Cross-shore distributions of time-averaged velocity, turbulent energy, bubble intensity and DCO_2 concentration



Estimation of gas transfer velocity in the surf zone

■Gas flax can be expressed as:

$$F = U\Delta C \qquad (1)$$

U: gas transfer velocity

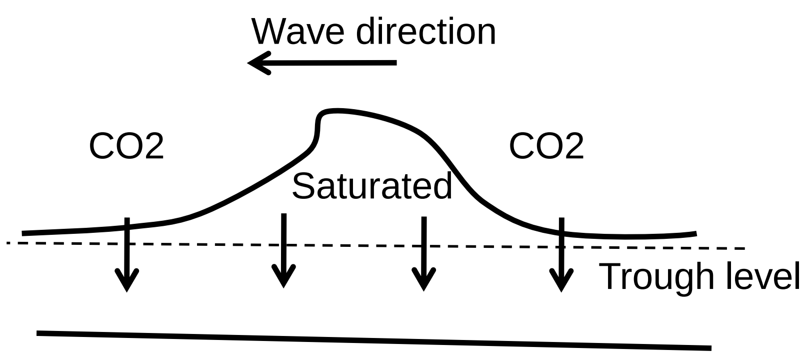
ΔC: difference of gas concentration across the water surface

■Assumption:
the region above wave trough level is saturated

$$\Delta C = C_s - C_f \qquad (2)$$

C_s: concentration above wave trough level (6%)

C_f: concentration under wave trough level



■Gas flax also can be expressed as:

$$F = \frac{dC}{dt}\Delta z \qquad (3)$$

Δz: turbulent mixing depth

■Assumption:

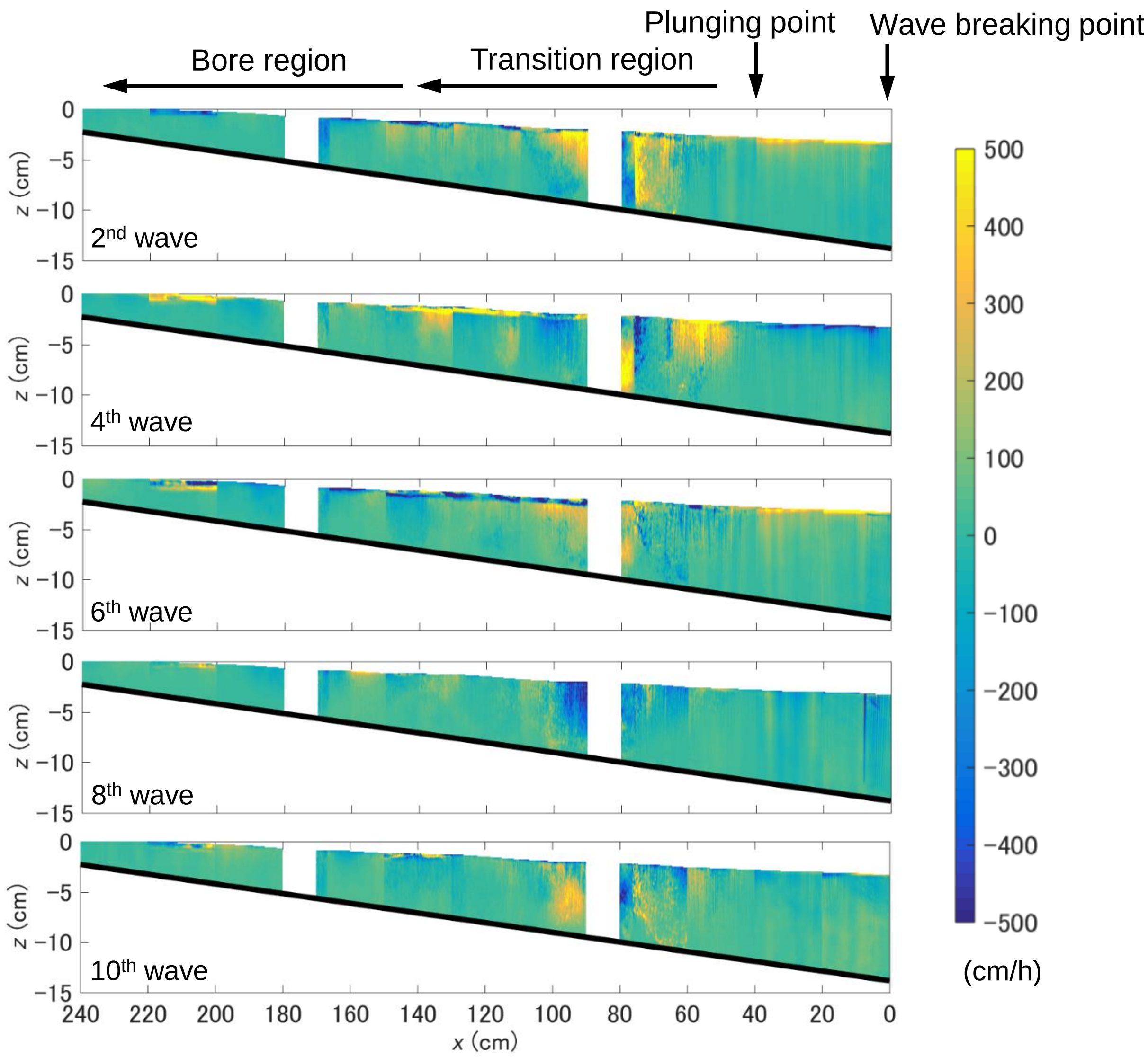
$$\Delta z \cong H \qquad (4)$$

H: wave height

■From eq.(1) to eq.(4), gas transfer velocity in a surf zone can be estimated in:

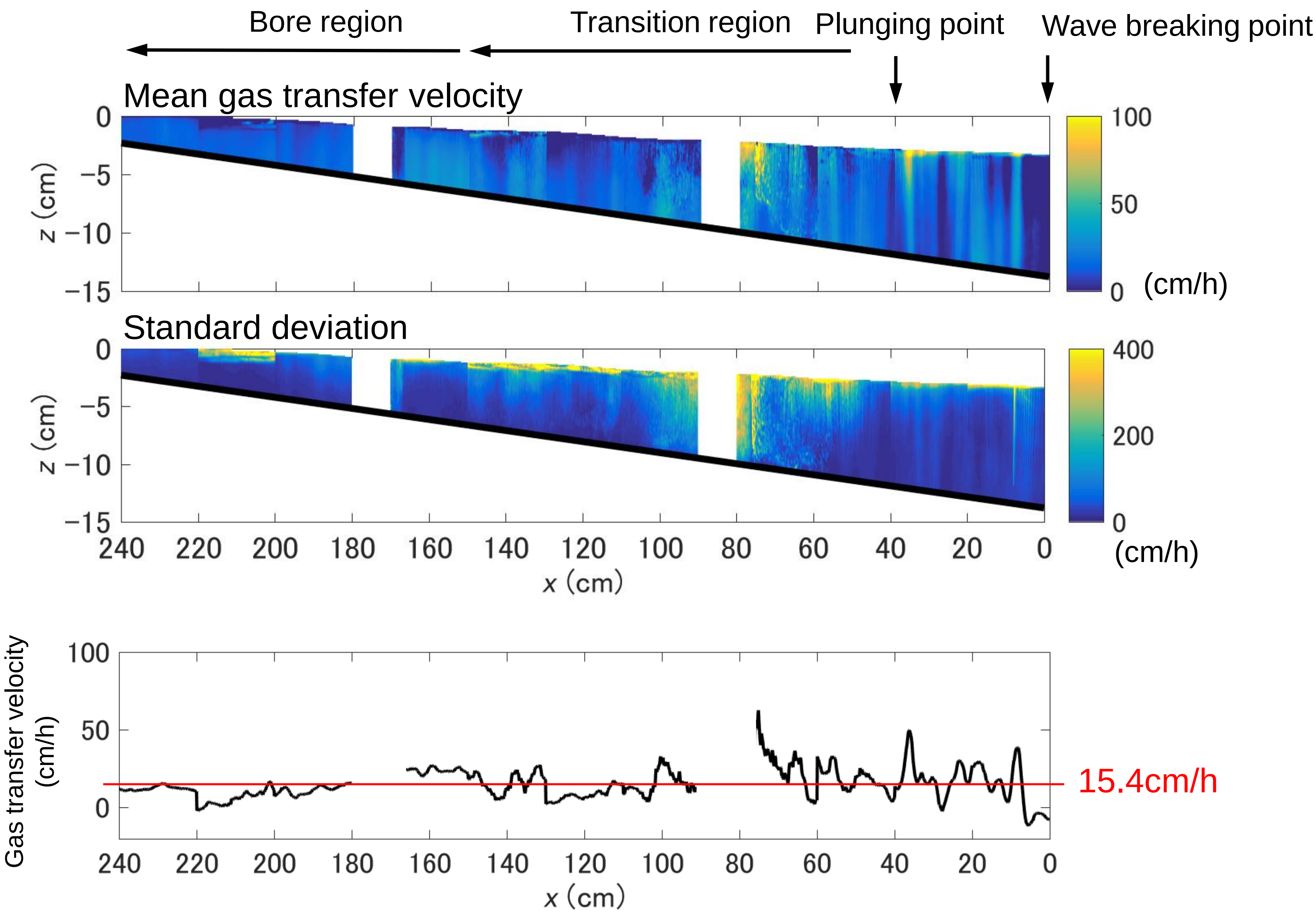
$$U = \frac{dC}{dt}\,\frac{H}{C_s - C_f} \qquad (5)$$

Gas transfer velocity in the surf zone



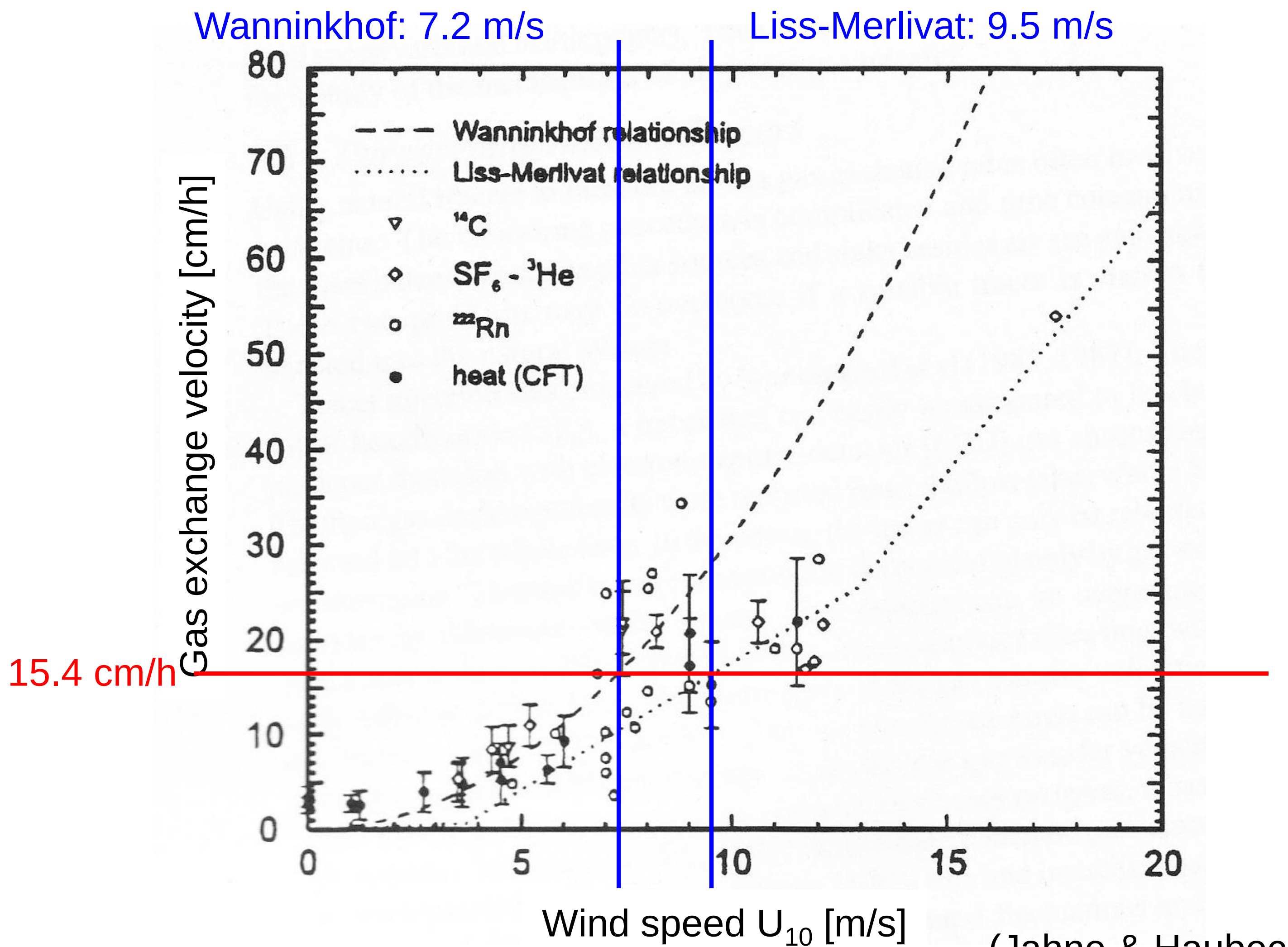
Gas transfer velocity in the surf zone

Mean gas transfer velocity averaged over 10 waves



Gas transfer velocity in a surf zone

Gas transfer velocity over the suf zone: 15.4 cm/h



(Jahne & Haubecker, Annu Rev Fluid Mech, 1998)

Conclusions

- DCO_2 concentration and air-water turbulent flow field in a surf zone were measured using LIF, PIV and LED backlight.

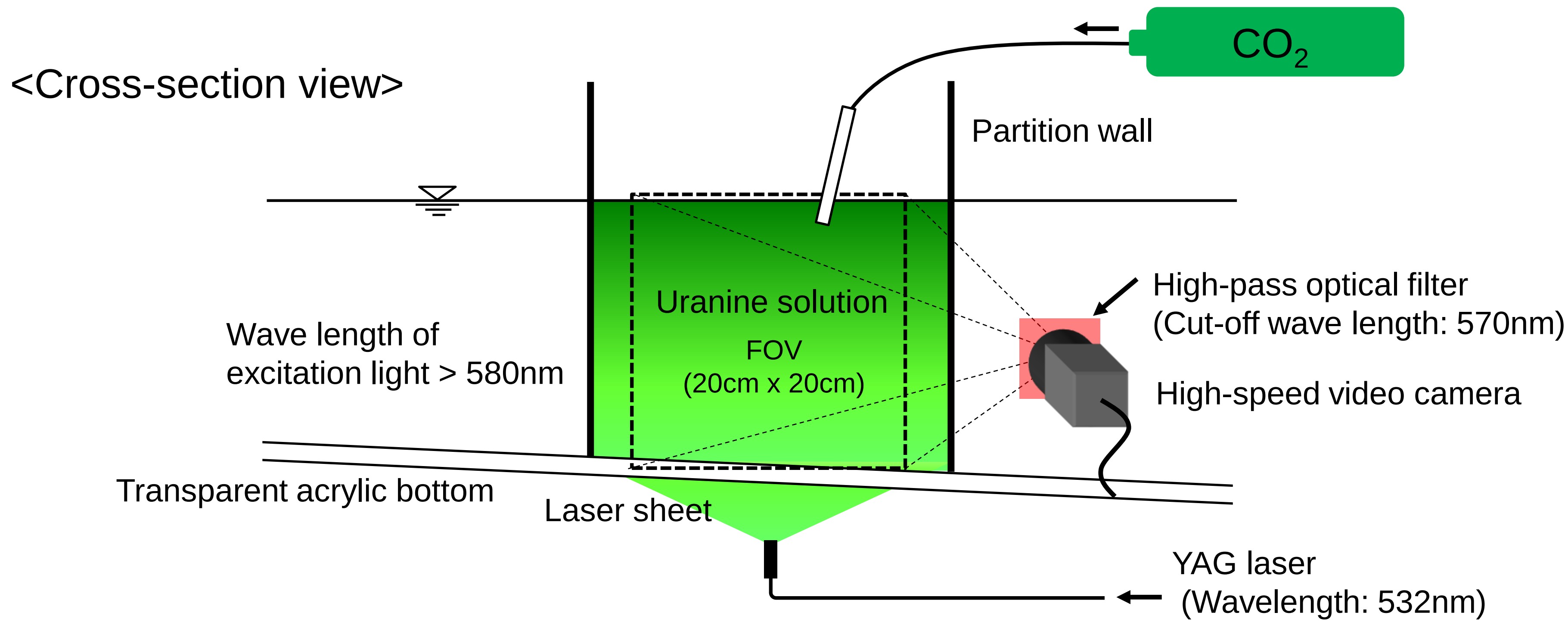
- In the transition region, local gas supply due to entrained bubbles was very active. However, spatial concentration does not increase in a short time because the local dissolved gas is mixed in the deep water mass by strong turbulence.

- In the bore region, the concentration increases in a short time because water is shallow. Undertow transports the concentrated DCO_2 toward the wave breaking point through near the bottom.

- While entrained bubbles and turbulent mixing have important roles in local gas transfer, undertow is contribute to the steady gas transfer from the bore region to the wave breaking point.

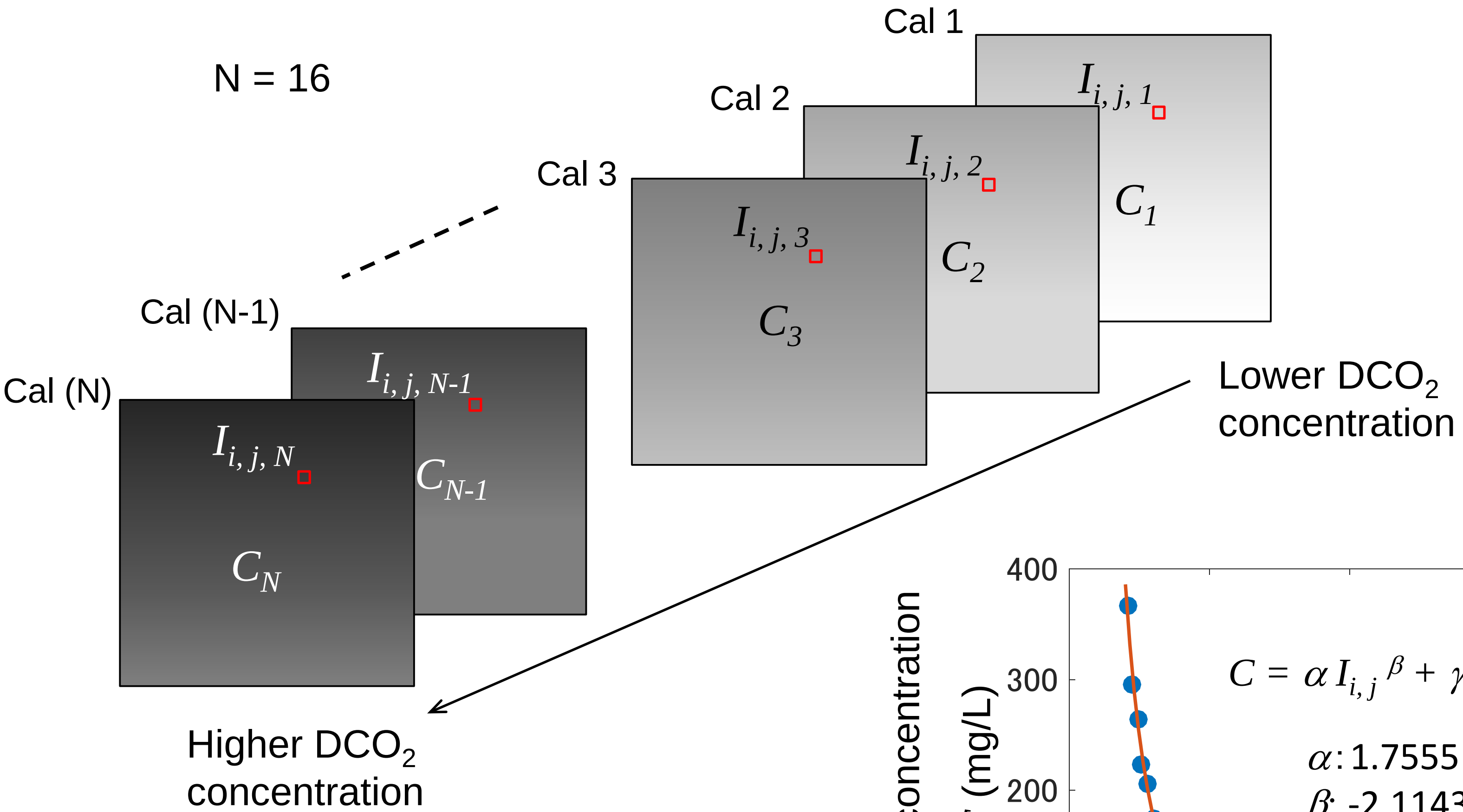
LIF measurement for DCO_2 concentration field

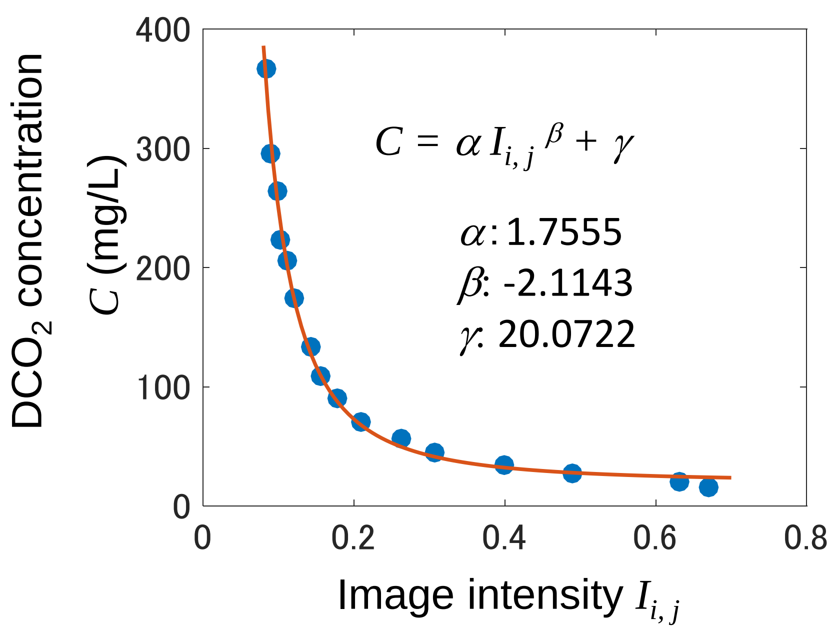
Calibration method



1. Adding CO_2 into water.
2. Stirring uranine solution until the fluorescence intensity became spatially uniform.
3. Measuring bulk DCO2 concentration using a grass electrode CO2 meter.
4. Recording an image of fluorescence intensity.

LIF measurement for DCO_2 concentration field





$I_{i,j}$: Fluorescence intensity at an individual pixel

C_n: Bulk DCO_2 concentration in a calibration area

Gas transfer velocity estimated from mean turbulent energy

Gas transfer velocity estimated from turbulent energy:

$$U = \sqrt{K}/S_c$$

K : Mean turbulent energy (cm^2/s^2).

S_c: Schmidt number (600).