Laboratory study on air-sea CO_2 exchange with wave breaking

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Contents

Background

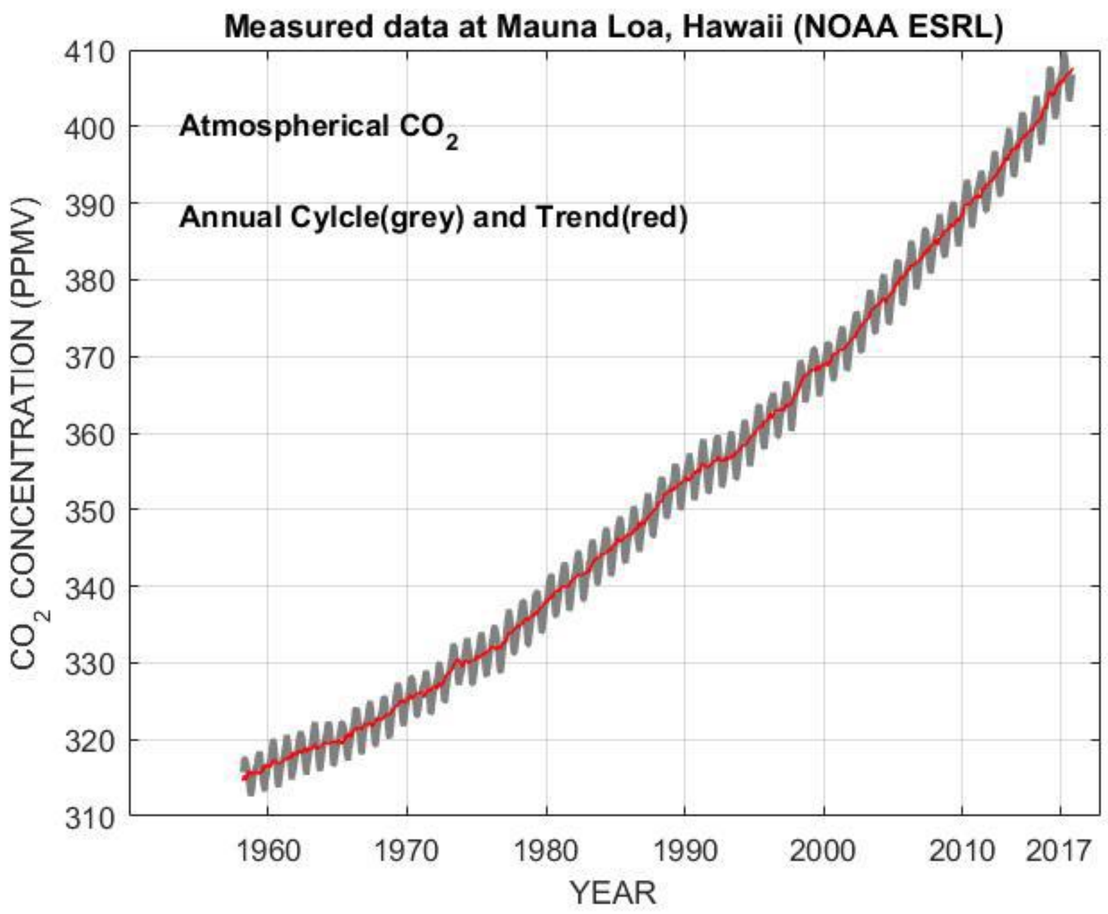
- CO_2 in atmosphere has been increasing since industrial revolution

- Ocean is a large dynamic reservoir of carbon cycle

  The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification, the pH of ocean surface water has decreased by 0.1 corresponding to a 26% increase in acidity. (IPCC, 2014)

- CO_2 transfer velocity affected by wave breaking

  "We find a general global trend of increasing values of wind speed and, to a lesser degree, wave height, over this period" (Young *et al.,* 2011)



Background

$$F = K_{co_2}(C_w - \alpha C_a)$$

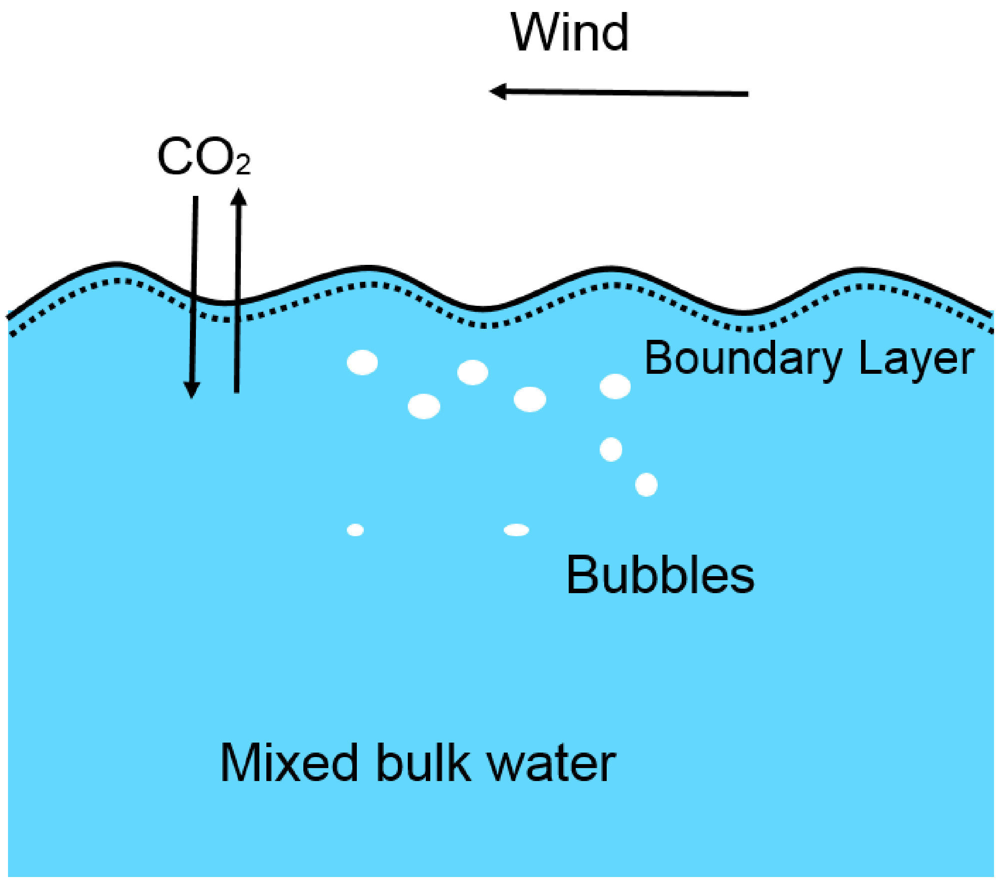
F : flux of gas transfer

K_{co_2} : gas transfer velocity

C_w : gas concentration in water

α: non-dimensional solubility of gas

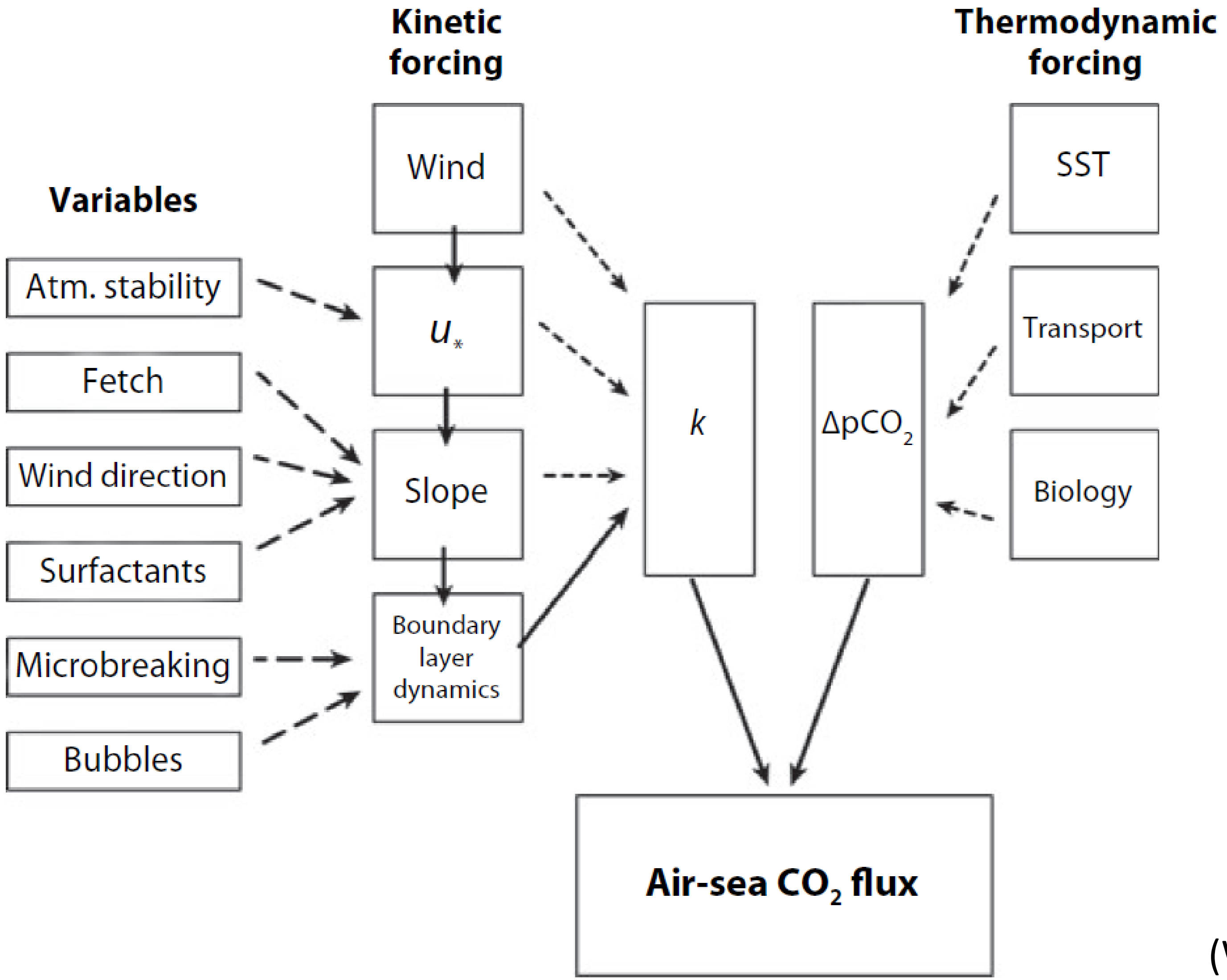
C_a : gas concentration in air



K_{co_2} :

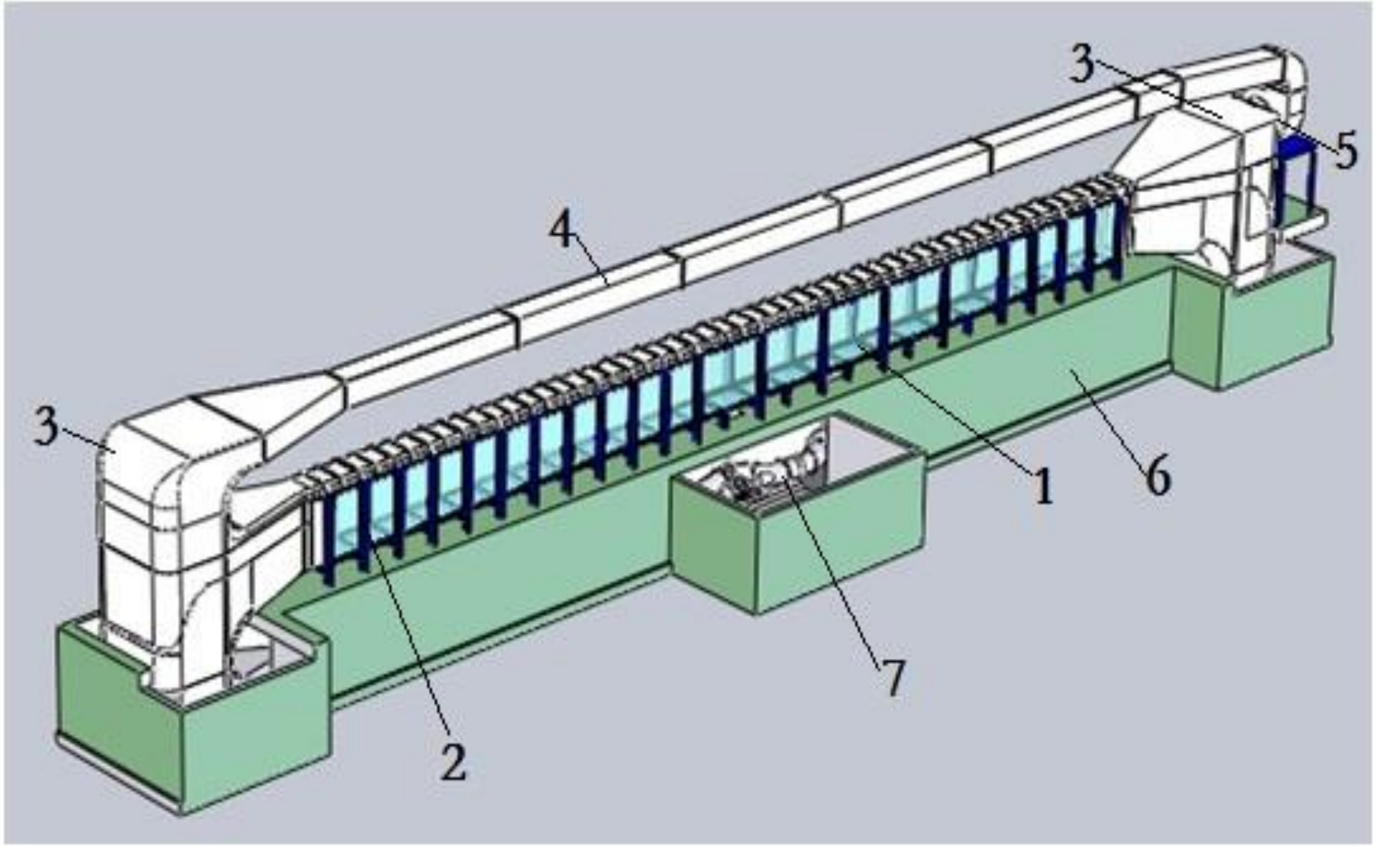
- Diffusion
- Turbulence
- Bubbles

Background



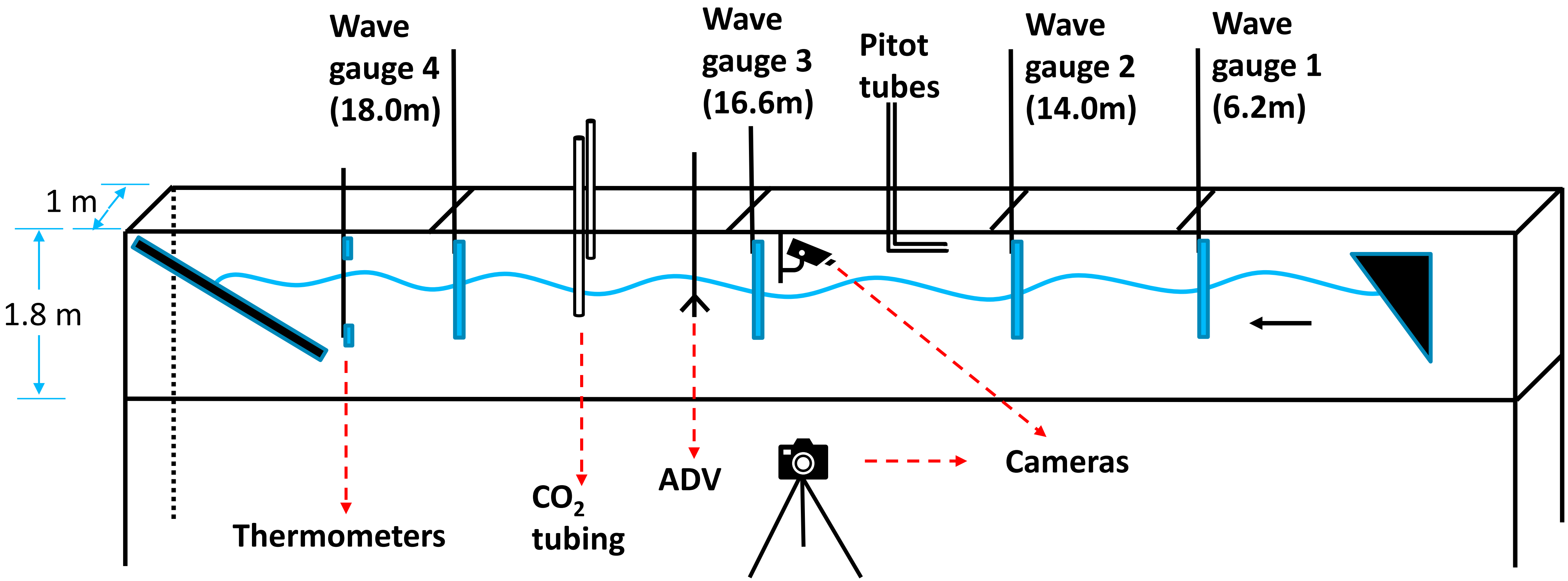
(Wanninkhof *et al.*, 2009)

Laboratory Experiment



The diagram of the wave tank. 1-Glasses； 2-Wavemaker； 3- Plenum chamber； 4-Wind channel； 5-Fan； 6-Tank foundation； 7-Water channel.

Laboratory Experiment



Laboratory Experiment

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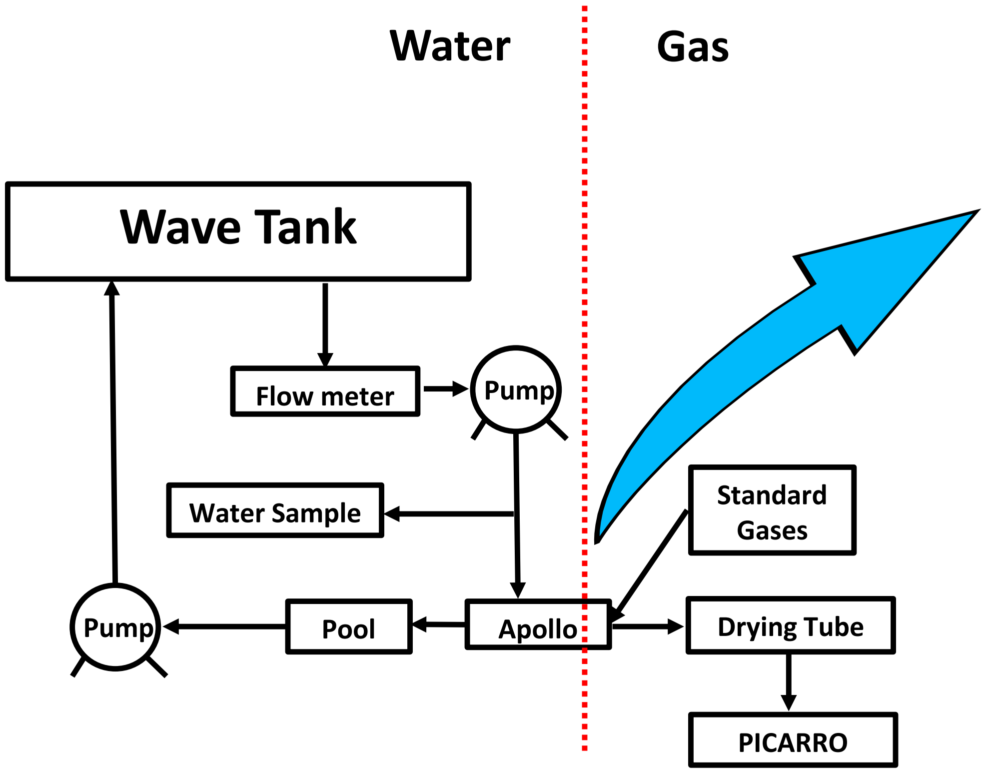
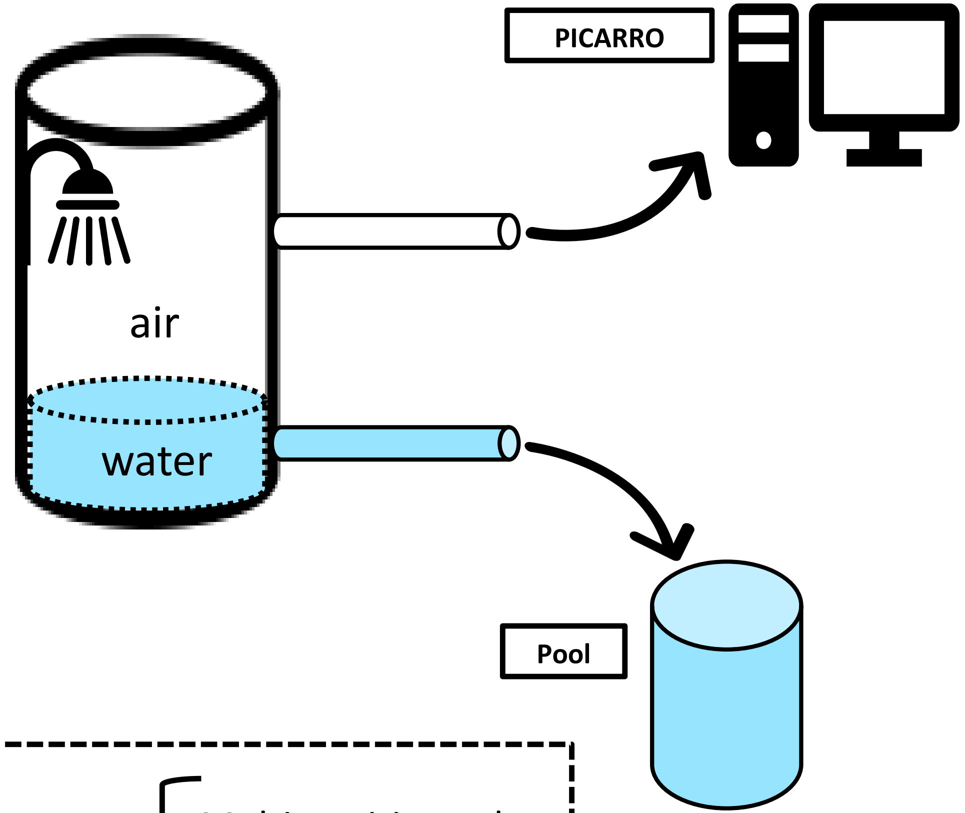
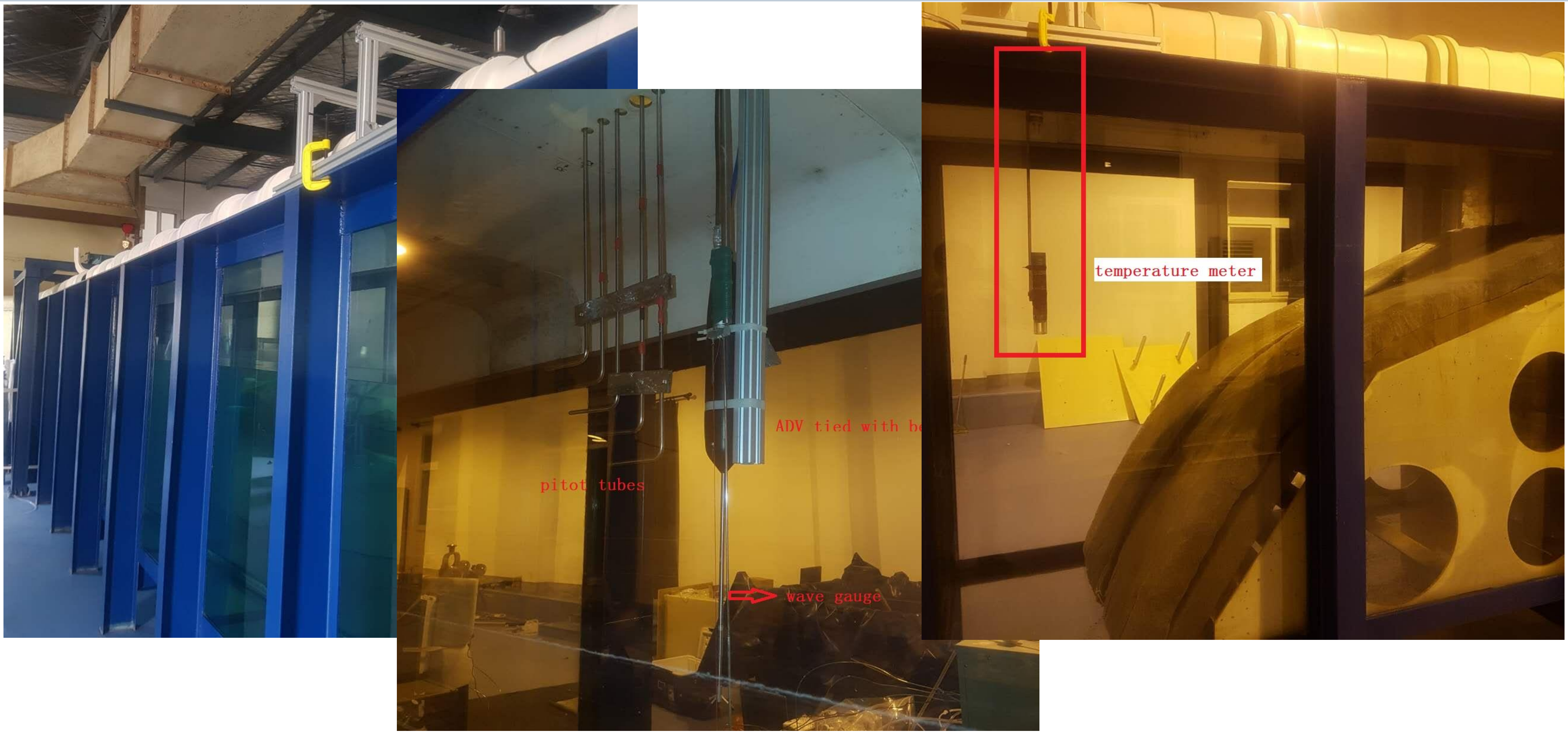




Apollo
- Multi-position valve
- CO_2 analyzer
- equilibrator

Laboratory Experiment



Laboratory Experiment

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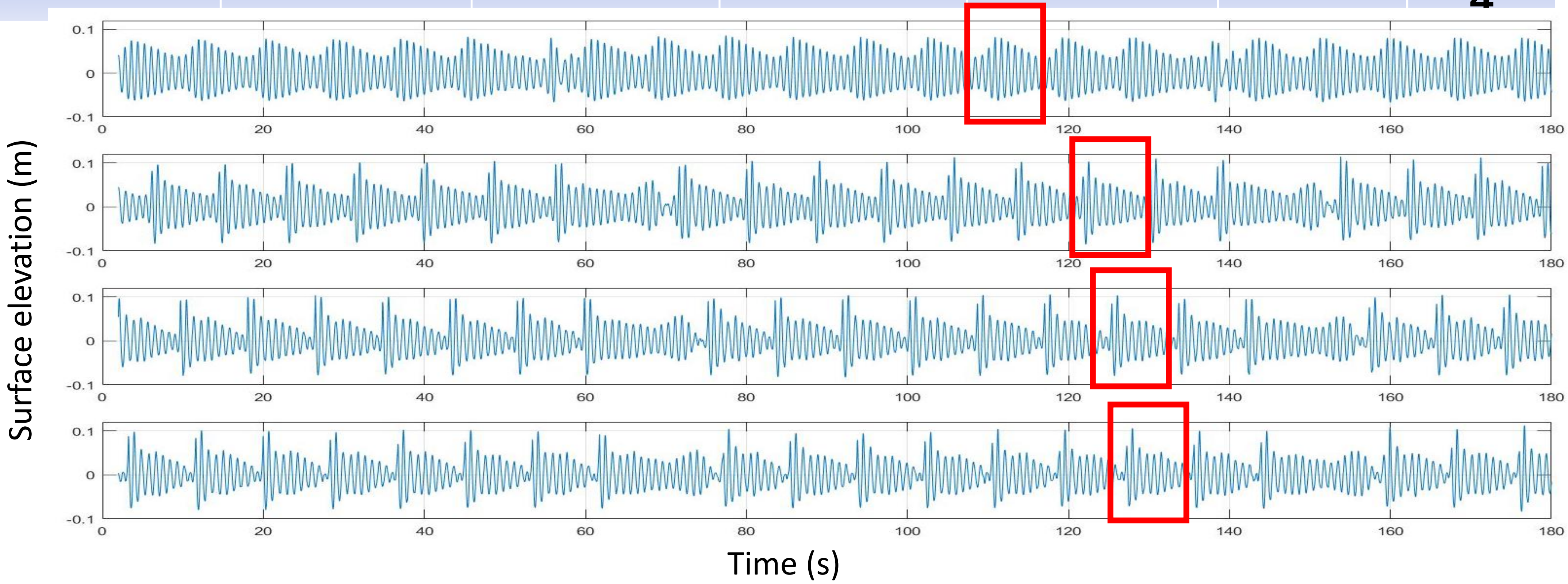
Carrier_wave frequency (HZ)	Amplitude (m)	Steepness	Sideband frequency (HZ)	Amplitude (m)	BFI
1.2	0.035	0.20	1.32	0.010	0.95
1.2	0.052	0.30	1.33	0.006	1.36
1.0	0.050	0.20	1.10	0.024	0.95
1.3	0.029	0.20	1.43	0.007	0.95
1.1	0.041	0.20	1.21	0.014	0.95
0.9	0.061	0.20	1.04	0.035	0.60
1.1	0.033	0.16	1.24	0.019	0.59
1.1	0.051	0.25	1.24	0.014	0.94
1.0	0.055	0.22	1.11	0.023	0.95
0.9	0.055	0.18	1.02	0.039	0.61

Laboratory Experiment

Carrier_wave frequency (HZ)	Amplitude (m)	Steepness	Sideband frequency (HZ)	Amplitude (m)	Df (HZ)	BFI
1.2	0.035	0.2	1.32	0.0102	0.12	0.9524



Laboratory Experiment

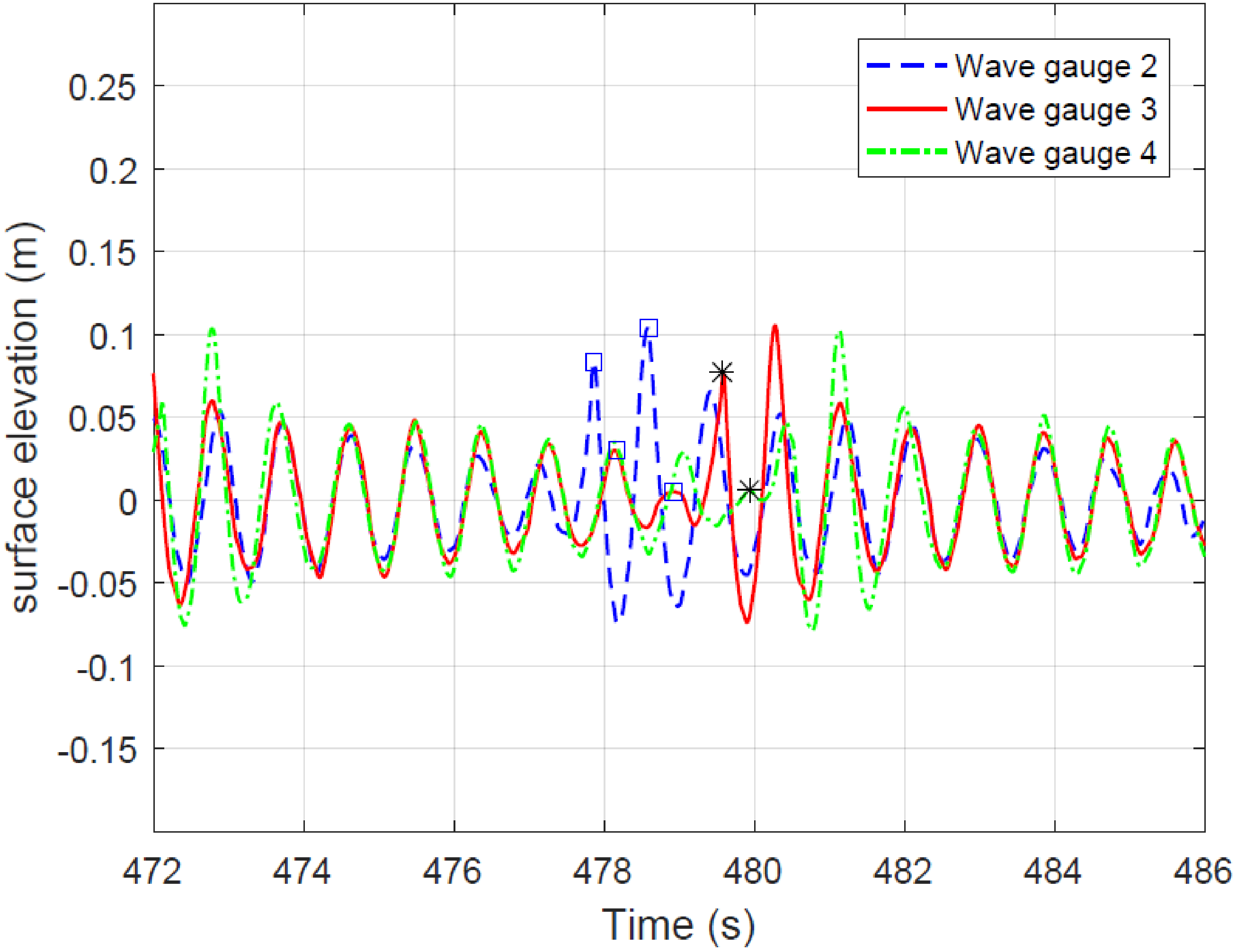
Wind forcing

Frequency (HZ)	U10 (m/s)
10	4.46
15	6.88
20	9.19
25	11.12
30	13.25
35	15.43

Monochromatic waves + Wind forcing

Carrier wave frequency (HZ)	Amplitude (m)	Sideband frequency (HZ)	Wind Frequency (HZ)	U10 (m/s)
0.9	0.055	1.02	25	11.21
0.9	0.055	1.02	15	6.77
1.1	0.041	1.21	20	9.14
1.1	0.041	1.21	30	13.43
1.0	0.055	1.11	20	8.85
1.0	0.055	1.11	30	13.43

Laboratory Experiment



1. For experiments with monochromatic waves (or with superimposed wind forcing), wave breaking events are recognized by comparing wave records at wave gauge 2, 3 and 4. The breakers at gauge 3 closest to CO_2 sampling tubing are evaluated.

2. For experiments with wind forced waves, wave breaking events at waves gauge 3 are identified by using the criterion that individual wave steepness ε = ak < 0.44 (Babanin *et al.* 2007, 2010).

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Calculate K_{CO_2}

$$\frac{\partial C_w}{\partial t} \cdot \frac{V_w}{A} = -K_{CO_2} \cdot (C_w - C_a)$$

(Ocampo-Torres *et al.*, 1994)

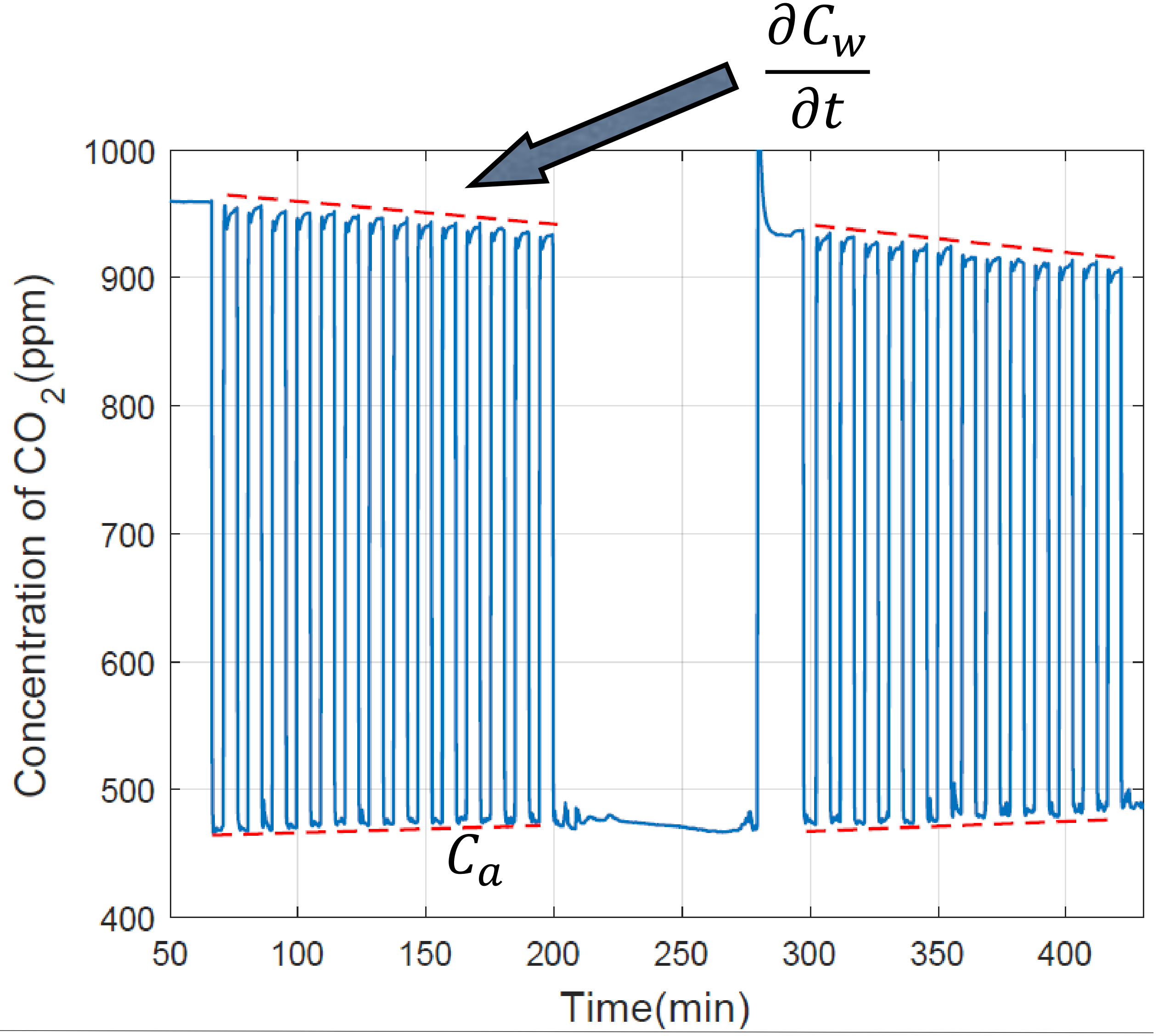
C_w: CO_2 concentration in water

V_w: Water volume

A: Area of water surface

K_{CO_2} : CO_2 gas transfer velocity

C_a: CO_2 concentration in air



Laboratory Experiment

$$\frac{\partial C_w}{\partial t} \cdot \frac{V_w}{A} = -K_{CO_2} \cdot (C_w - C_a)$$

$\boldsymbol{\frac{V_w}{A}}$, choose mean wave height of breaking waves near sampling tubing (deep water waves).

For shallow water waves, $\boldsymbol{\frac{V_w}{A}}$ is water depth

K_{CO_2} → K_{600}

$$\frac{K_{600}}{K_{co_2}} = \left(\frac{Sc_{600}}{Sc}\right)^{-0.5}$$

(Jahne *et al.* 1987)

$$\mathrm{Sc} = \frac{\nu}{D} \qquad Sc_{600} = 600$$

K_{600}, gas trasfer velocity at 20 °C

ν, kinematic viscosity

D, mass diffusivity

Experiment with monochromatic waves

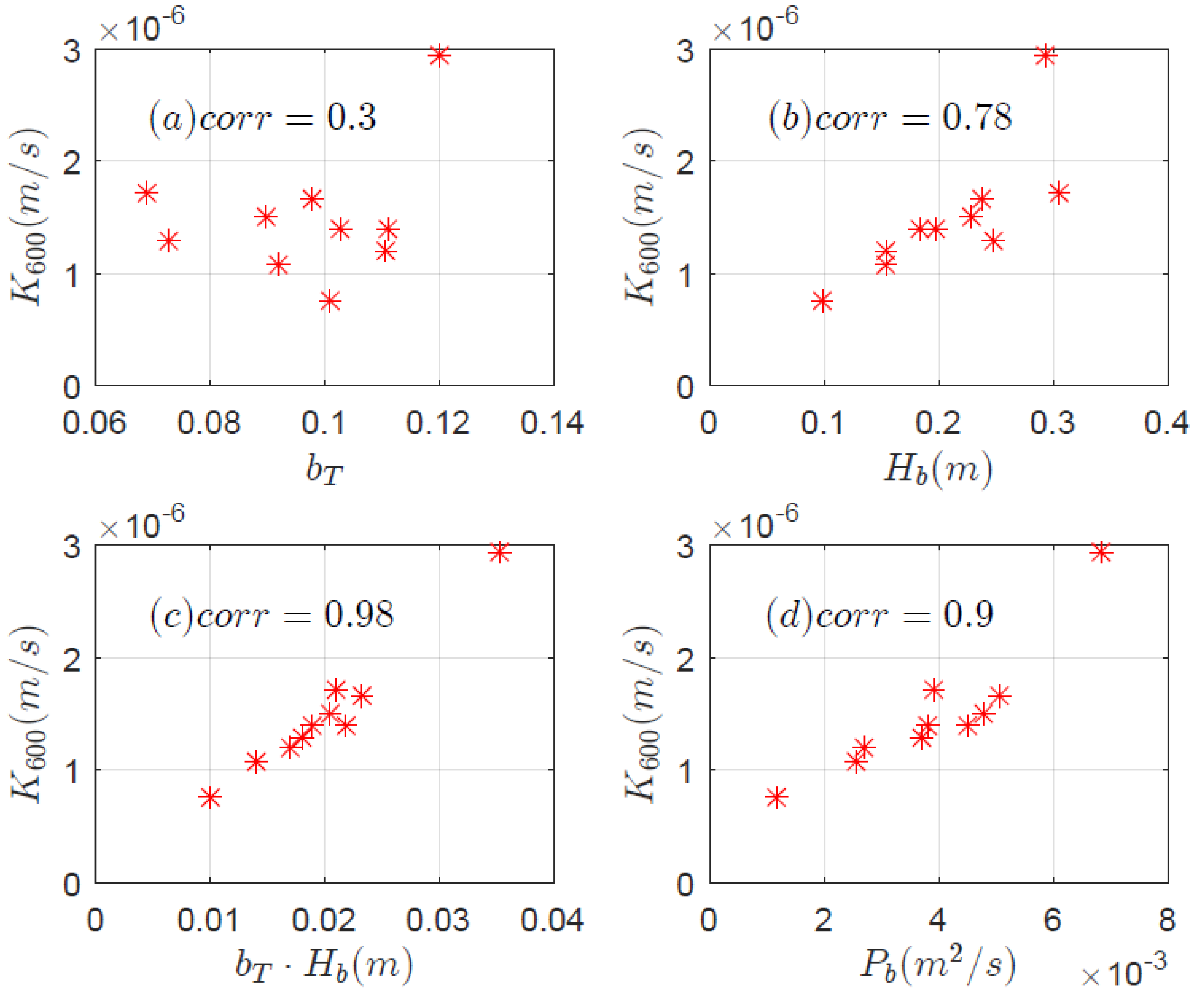
K_{600}, corrected co_2 gas transfer velocity

H_b, mean wave height of breakers.

b_T , Wave breaking probability.

$$P_b = \frac{\sum(H_{b1}^2 - H_{b2}^2)}{\Delta t},$$

the rate of the mean energy loss during experimental time length.



Results

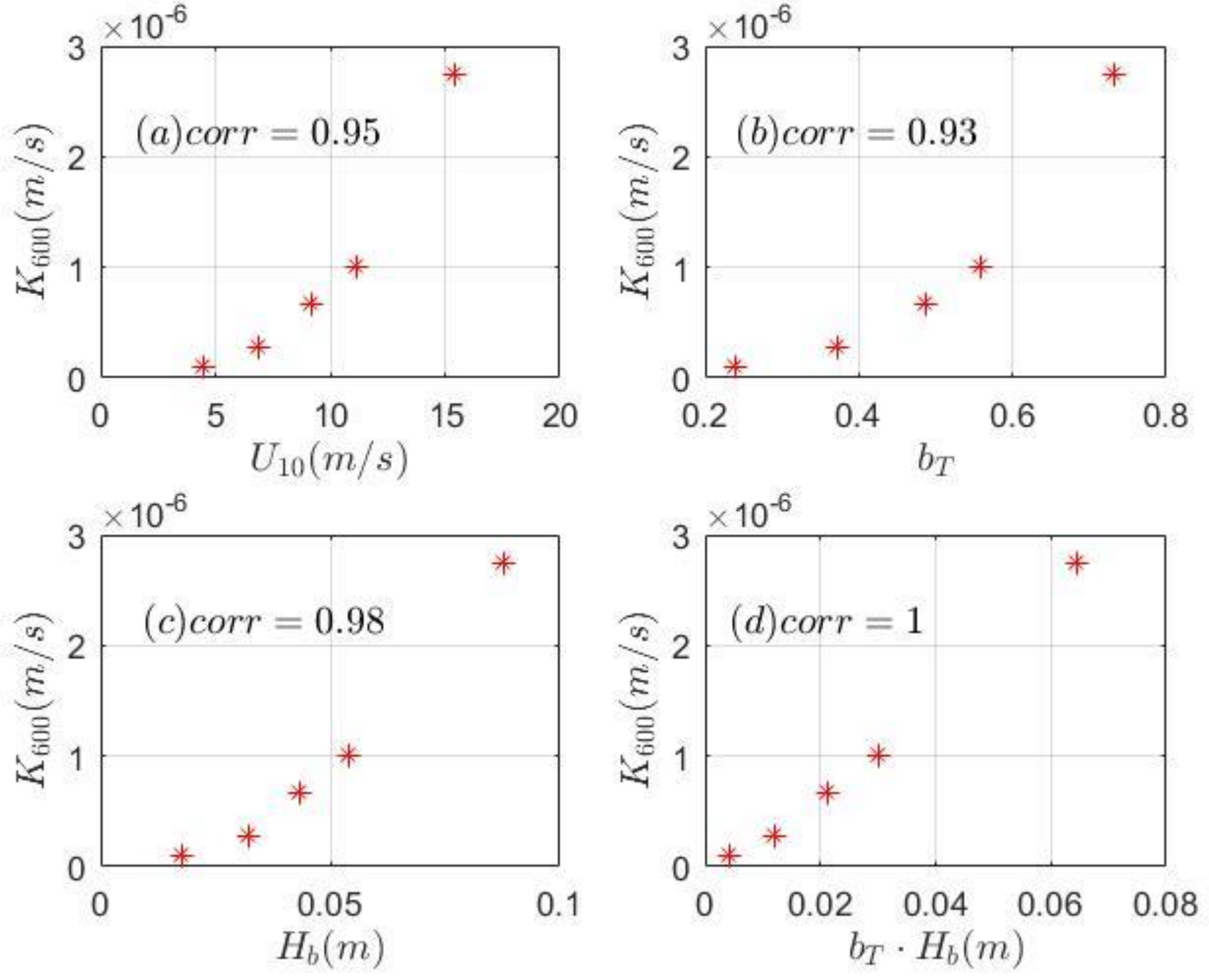
Experiment with wind waves

K_{600}, corrected co_2 gas transfer velocity

U_{10}, 10-meter wind velocity

H_b, mean wave height of breakers.

b_T , Wave breaking probability.



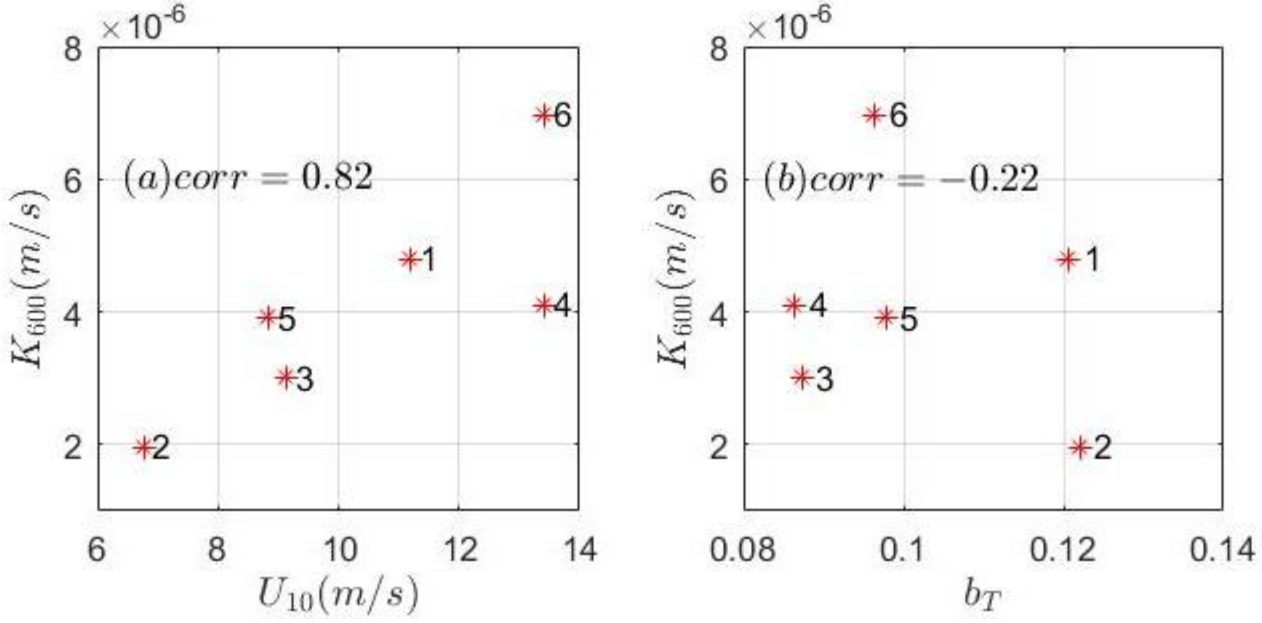
Experiment with monochromatic waves and wind forcing

K_{600}, corrected co_2 gas transfer velocity

U_{10}, 10-meter wind velocity

b_T , Wave breaking probability.

1. Modified breaking probability
2. Corrugated surface of non-breaking waves



Results

$$\widetilde{K} = \frac{K_{600}}{U_{wm}},\ R_{HW} = \frac{H_b \cdot U_{wb}}{\nu},$$

$$\widetilde{U} = \frac{U_*}{\sqrt{g \cdot H_s}}$$

K_{600}, corrected co_2 gas transfer velocity

b_T , wave breaking probability.

U_{wm}, mean wave orbital velocity

U_{wb}, mean wave orbital velocity of breakers

H_b, mean wave height of breakers.

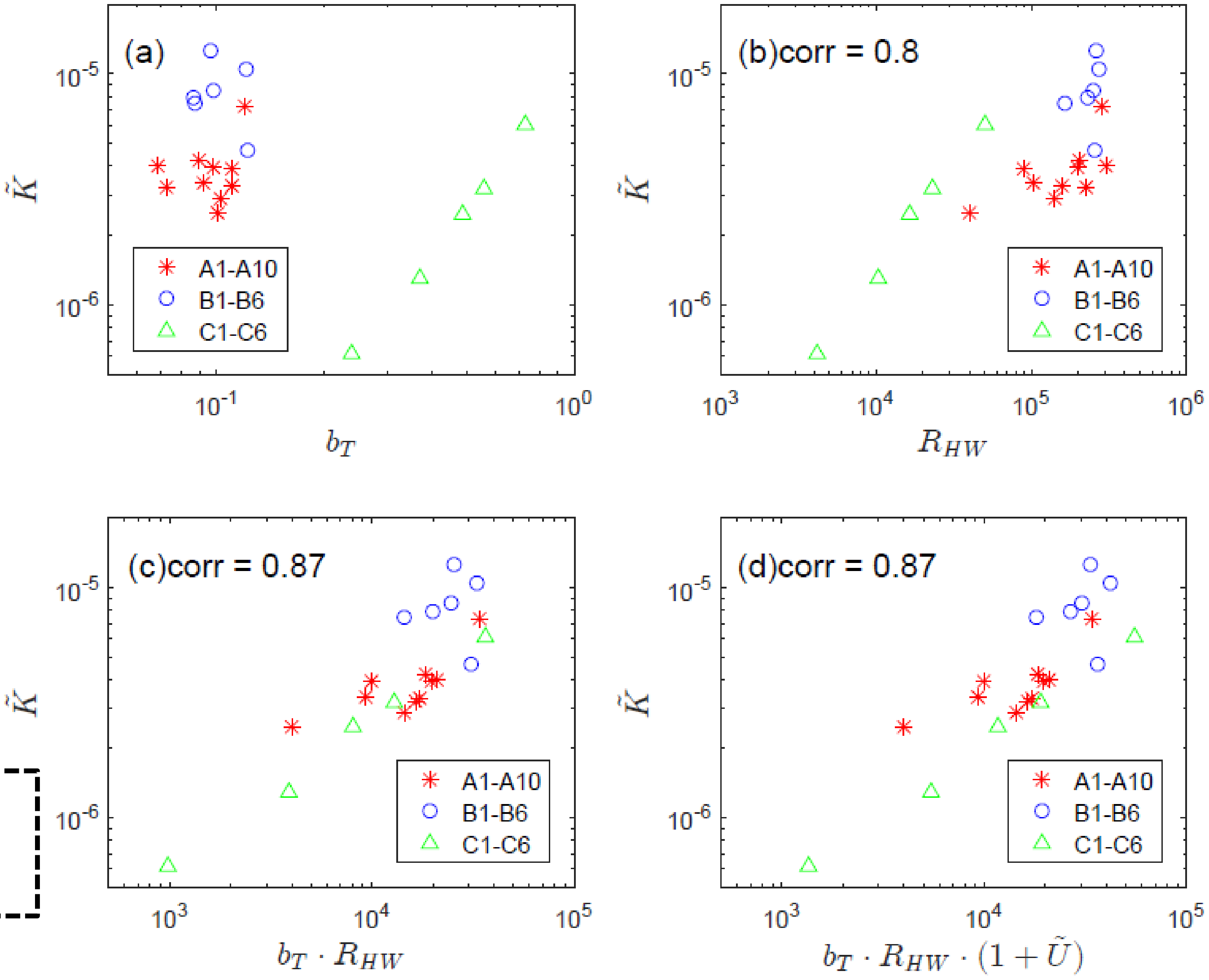
ν, water kinematic viscosity

U_*, wind friction velocity

H_s, significant wave height

g, gravitational acceleration

A1-A10: Monochromatic wave Exp.
B1-B6: Coupled wave Exp.
C1-C6: wind wave Exp.



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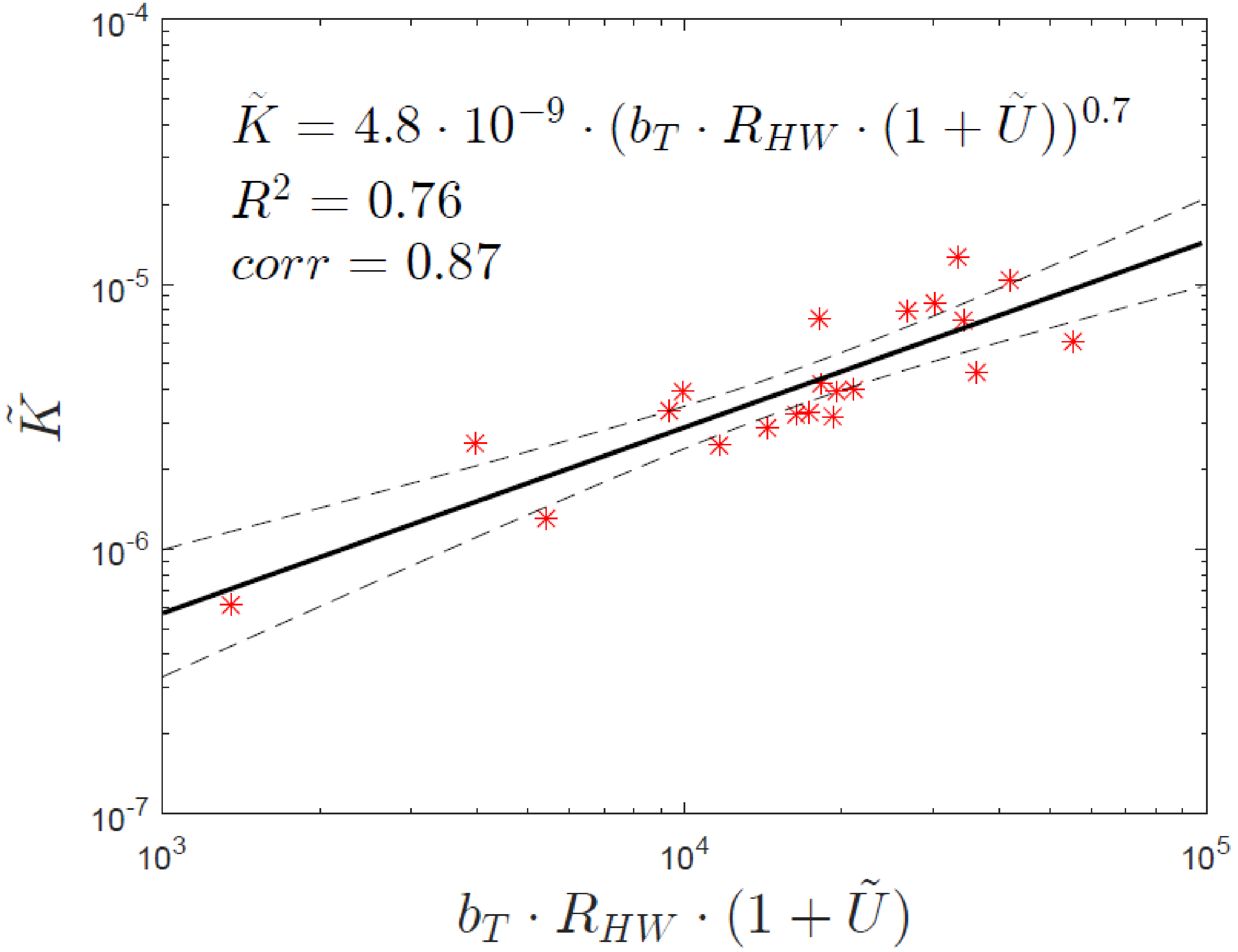

Summary

1. CO_2 gas exchange is closely related with wave breaking even without existence of wind.

2. CO_2 gas exchange is enhanced by wind when it is forced on top of waves.

3. CO_2 transfer rate can be expressed as a function of wave breaking probability, a modified Reynolds number and an enhancement factor to account for wind speed.