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Wave-Coupled Effects in the CO2 Exchange and Spray Production near the Ocean Interface

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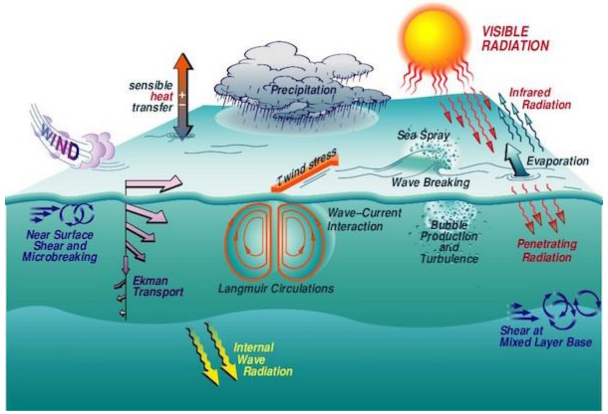
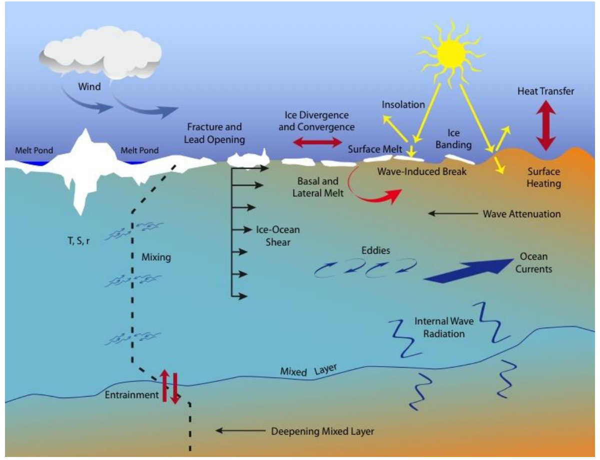
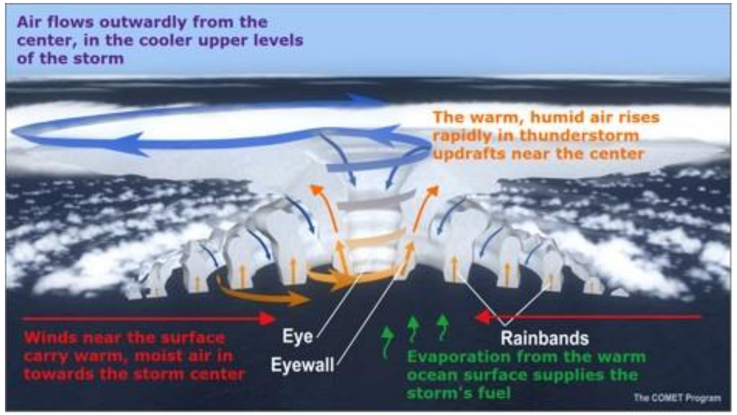
Waves as Atmosphere/Ocean Link





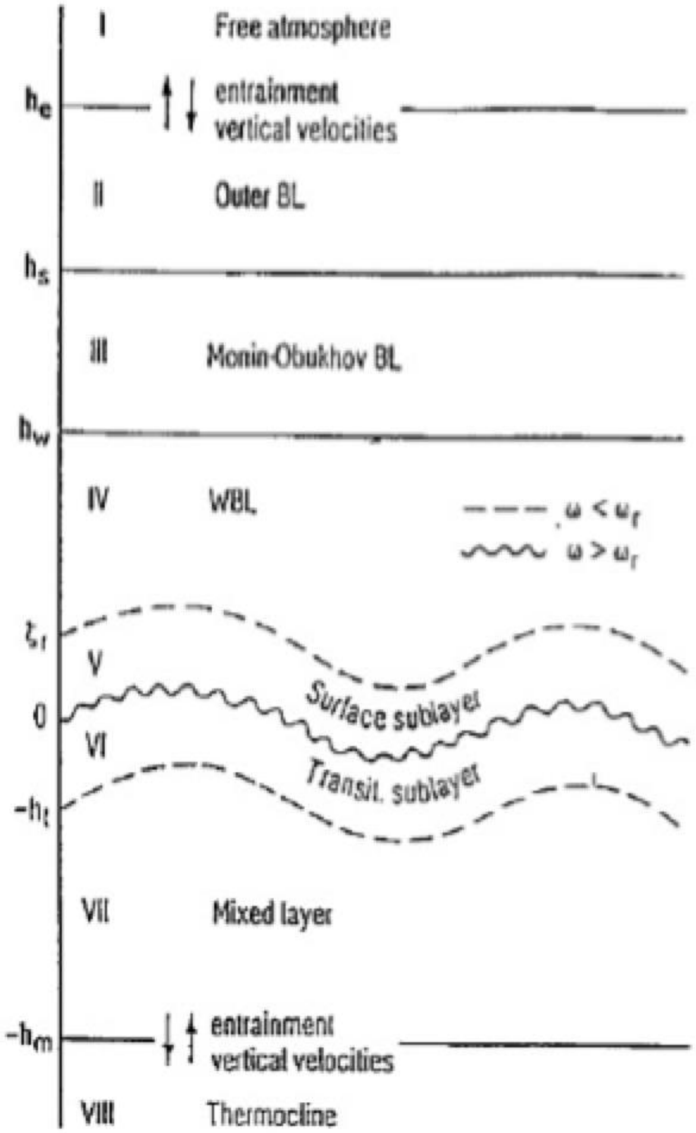


Small/large-scale air-sea processes are essentially but not in the models

- Atmospheric boundary layer
  - winds generate waves
  - waves provide surface roughness and change the winds
  - waves evolve, fluxes change
  - *waves generate spray*
- Upper ocean mixed layer
  - waves generate currents
  - produce turbulence
  - turbulence: facilitates mixing
  - changes the circulation, SST, nutrient transport
  - *facilitate gas exchange*

Tradition and future

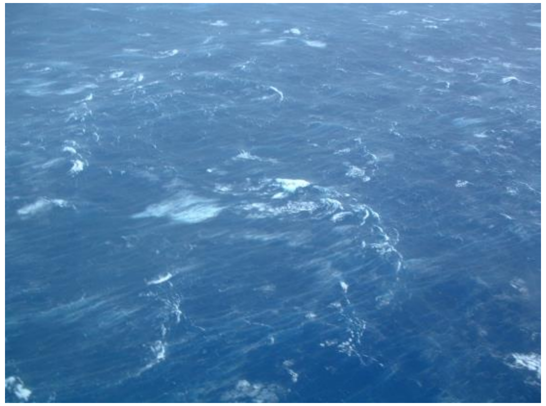
- Small scales and large scales are separated. Models reach saturation in their performance
- They need to be coupled, from turbulence to climate. Understanding exists, computer capacity exists

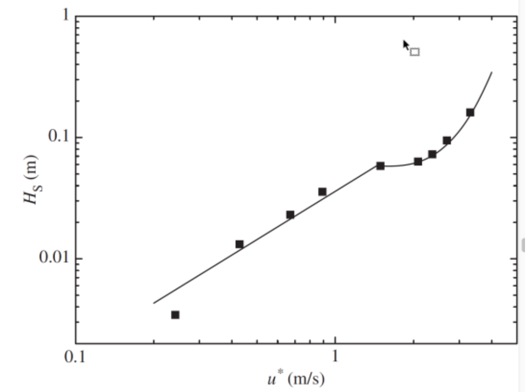


Chalikov & Belevich, 1993, BLM

everything changes at extreme conditions

- At wind speeds *U_{10}>32m/s,* dynamics of the atmospheric boundary layer, of the ocean wave surface and of the upper ocean layer – all change
- At the surface, at *U_{10}~34m/s:*
- wave asymmetry saturates *(Leikin et al., 1995, NPG),* wave breaking happens due to a different reason
- mass transfer velocity and volume flux of droplets increase sharply (*Iwano et al., 2013, Tellus B)*
- Sea drag saturates at *U_{10}=32-33m/s* above the surface *(Powel et al., 2003, Nature)*
- Cross-interface gas fluxes still grow, but at a slow rate if *U_{10} > 35m/s,* additional mechanisms become active below the surface *(McNeil & D'Asaro, 2007, J. Mar. Scie)*
- ***Simultaneous change of the regime in all the three air-sea environments means they are principally coupled***





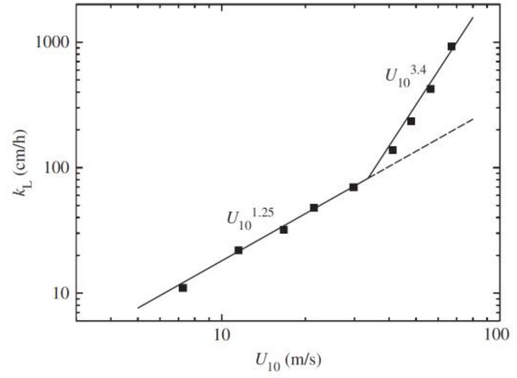


Fig. 3. Mass transfer velocity k_L against wind speed at 10 m height U_{10}.

Wave-coupled CO2 exchange

Slides of Shuo Li

Background

- CO_2 in atmosphere has been increasing due to anthropogenic activity

- 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 flux is affected by ocean wind and waves

  "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)

Motivation

- CO_2 transfer velocity is typically expressed in terms of linear, quadratic, or cubic wind speed. Gaps exist among these parameterizations

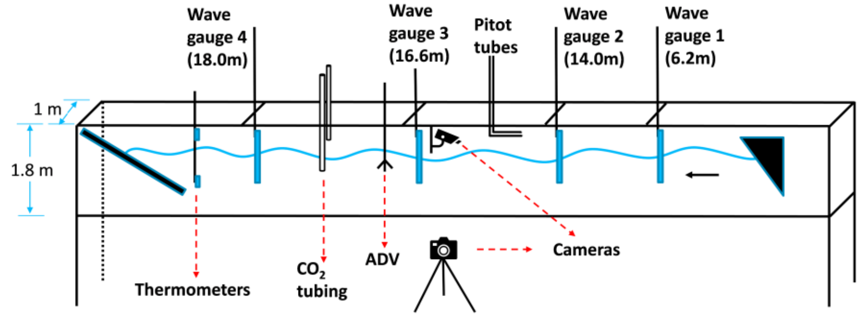
- CO_2 transfer is affected by turbulent intensity in water. Near surface turbulence can be significantly enhanced by waves and wave breaking

- CO_2 transfer velocity can be parameterized based on wave mechanisms

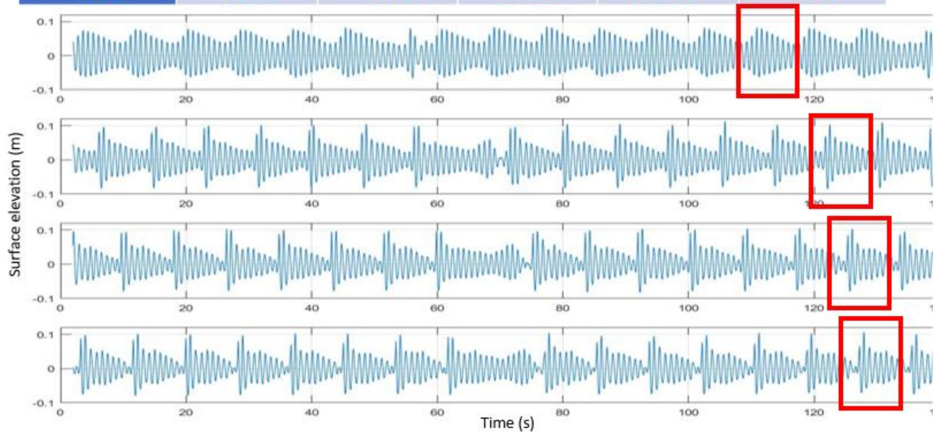
- Dimensionless formula should be able to reconcile CO_2 transfer under laboratory and field waves

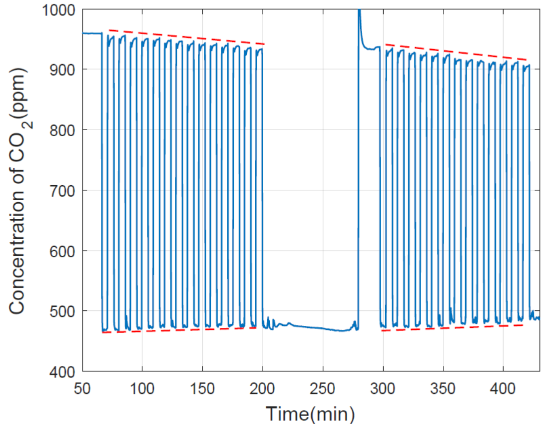
Laboratory Setup

- Wave input:
    A. Modulational wave trains generated by wave maker (no wind)
    B. Modulational wave trains coupled with superimposed wind
    C. Wind generated waves with 10-m wind speed 4.5-15.5 m/s
- Measurements:
    1. Wind speed, water surface elevation
    2. CO_2 concentration change the in air (lower profile)/water (upper profile)
    3. Camera/video recording, temperature, air pressure



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





Laboratory Experiment

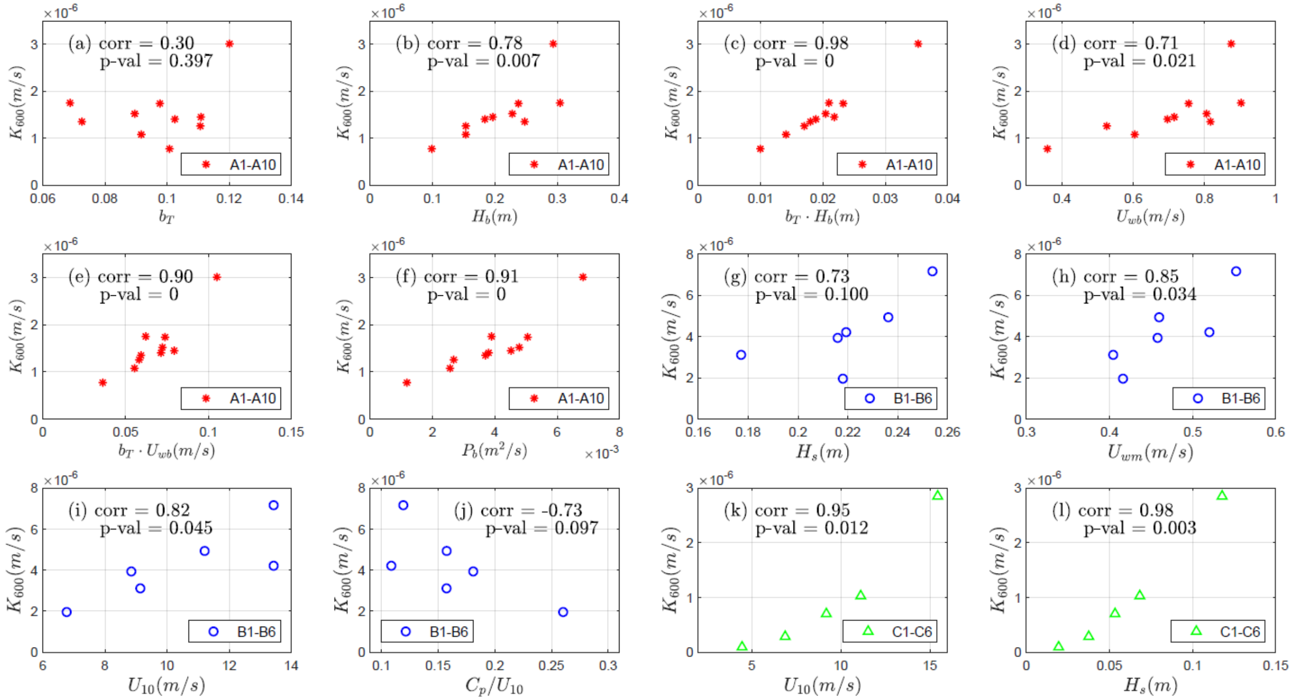
A1-A10: Modulational wave Exp.
B1-B6: Coupled wave Exp.
C1-C6: wind generated wave Exp.

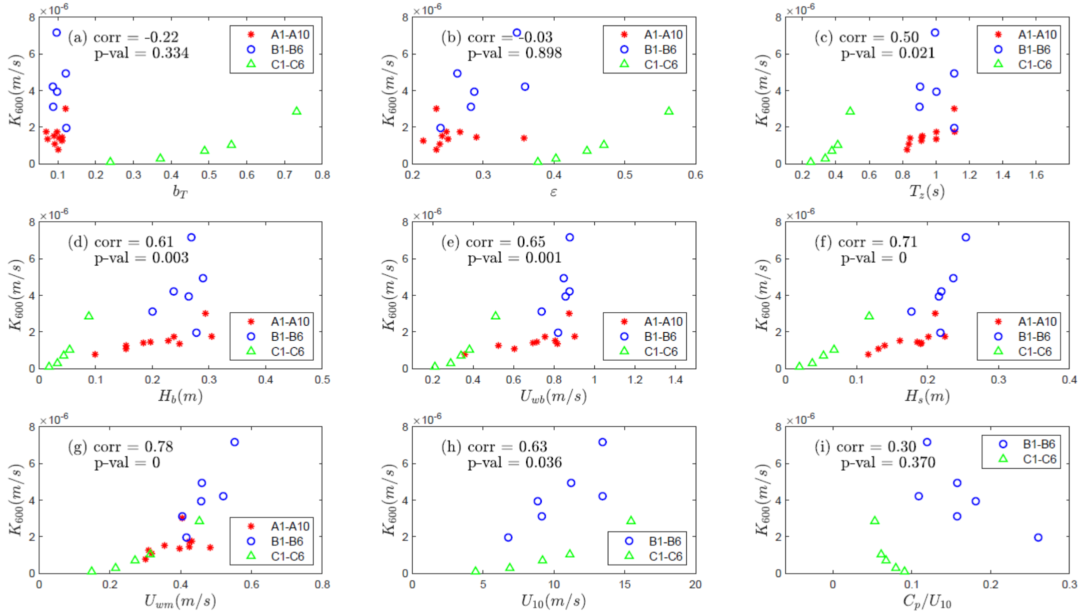
- Results:

  1. For individual groups of experiments (*upper figure*), breaking probability b_T in combination with breaking wave height and orbital velocity can strengthen the correlations (*panel c and panel e*) for breaking waves without wind.

  2. For all groups of experiments, wave orbital velocity and wave height are good parameters for scaling CO_2 gas transfer velocity in panel d-g (lower *figure*)

Li *et al., JPO (2021)*





- Dimensionless scaling

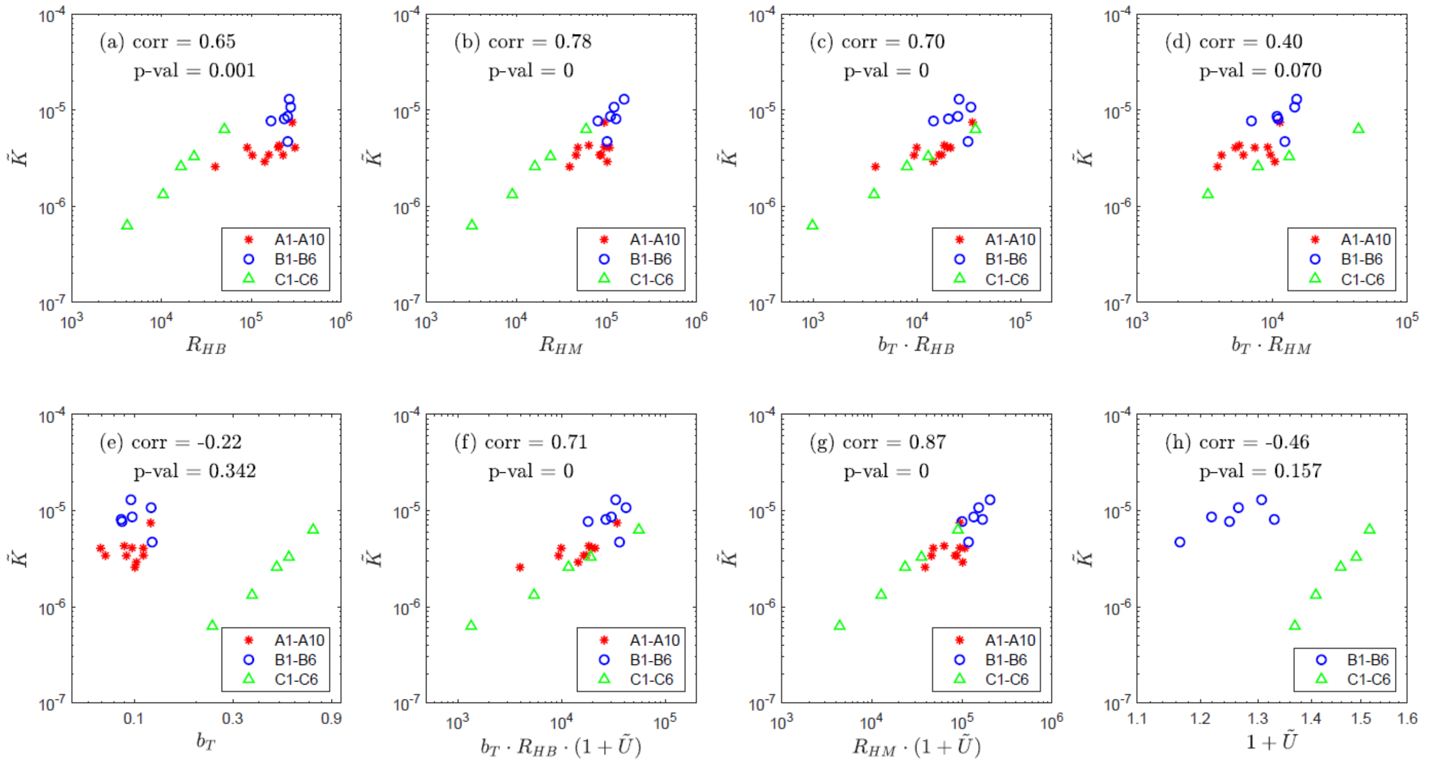
$$\widetilde{K} = \frac{K_{600}}{U_{wm}},\ R_{HB} = \frac{H_b \cdot U_{wb}}{\nu},$$

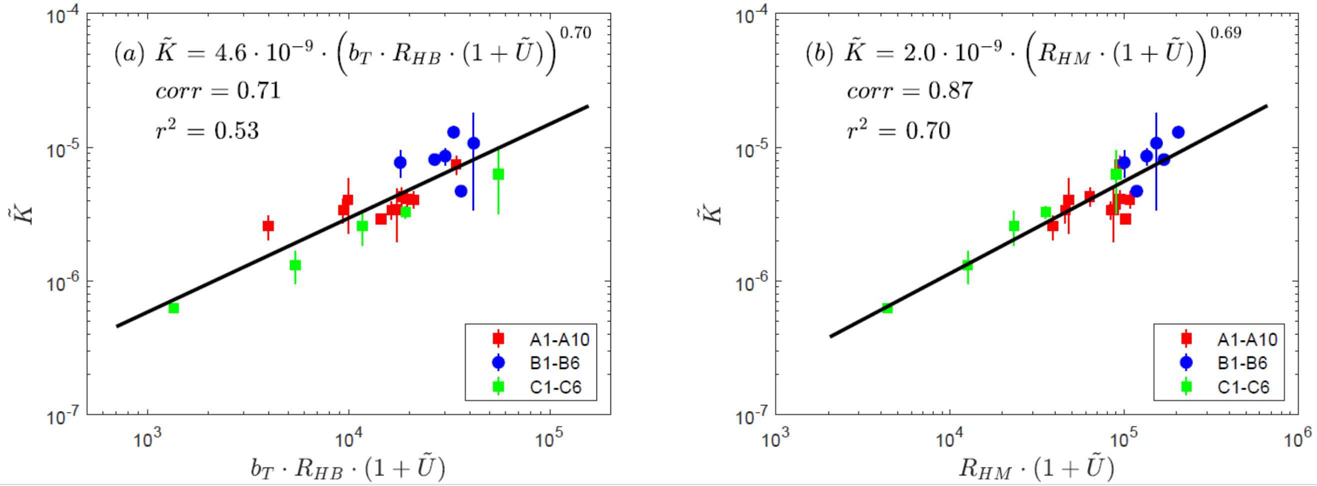
$$\widetilde{U} = \frac{U_*}{\sqrt{g \cdot H_s}},\ R_{HM} = \frac{H_s \cdot U_{wm}}{\nu}$$

$\widetilde{K}$, nondimensional co_2 transfer velocity
R_{HB}, R_{HM}, wave related Renolds Number
$\widetilde{U}$, nondimensional wind component
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

- Laboratory formula

1. Dimensionless velocity $\widetilde{K}$ is well correlated with $R_{HM} \cdot (1 + \widetilde{U})$
2. $\widetilde{K}$ is also fitted with $b_T \cdot R_{HB} \cdot (1 + \widetilde{U})$





Field Campaign Data

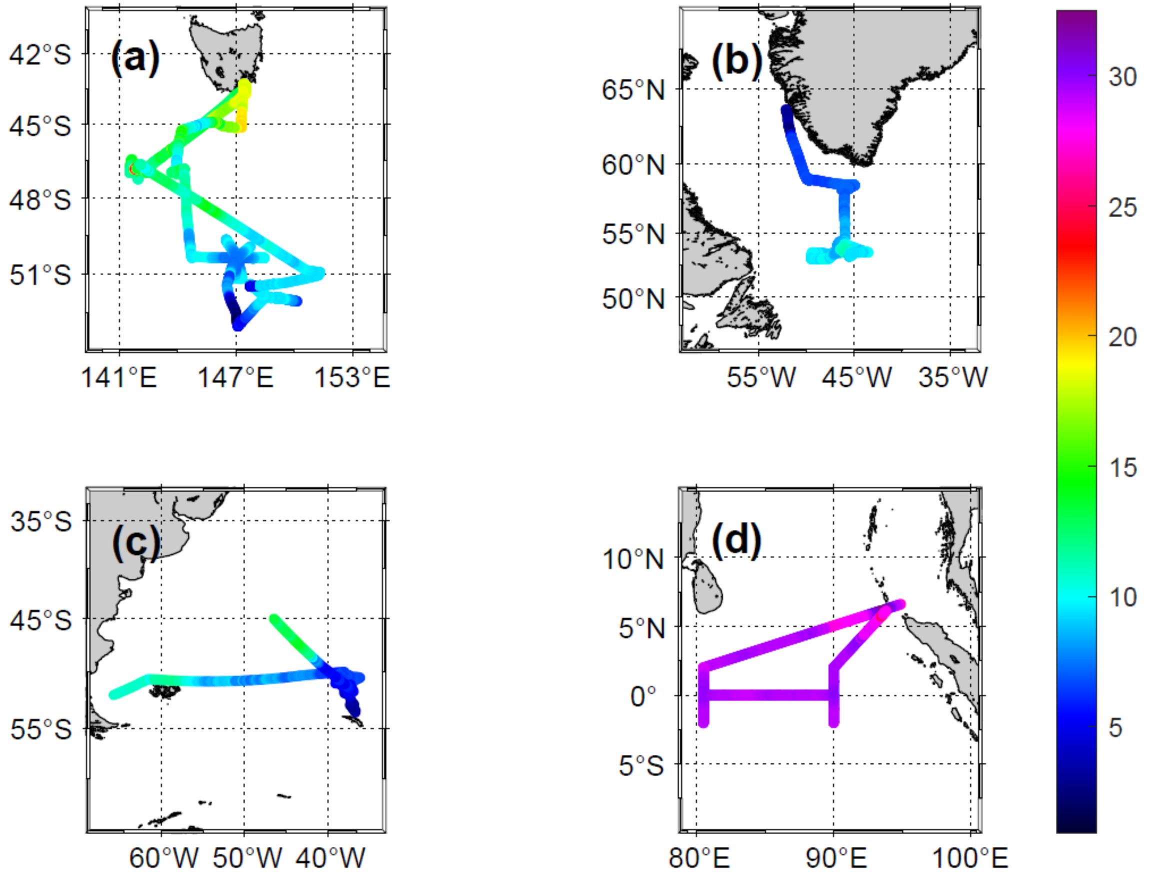
- Campaigns

(a). Capricorn 2016 (Southern Ocean)

(b). HIWINGS-The High Wind Gas Exchange Project 2013 (Northern Atlantic Ocean)

(c). SOGAS-Southern Ocean Gas Experiment 2008 (Southern Ocean)

(d). DYNAMO 2011 (Tropical Indian Ocean)



- Measurements

1. CO_2 gas flux through Direct Covariance method, CO_2 partial pressure through underway equilibrator system

2. Wave profile through Riegl laser altimeter, wind speed through sonic anemometer

3. Other environmental factors, such as SST, pressure, humidity

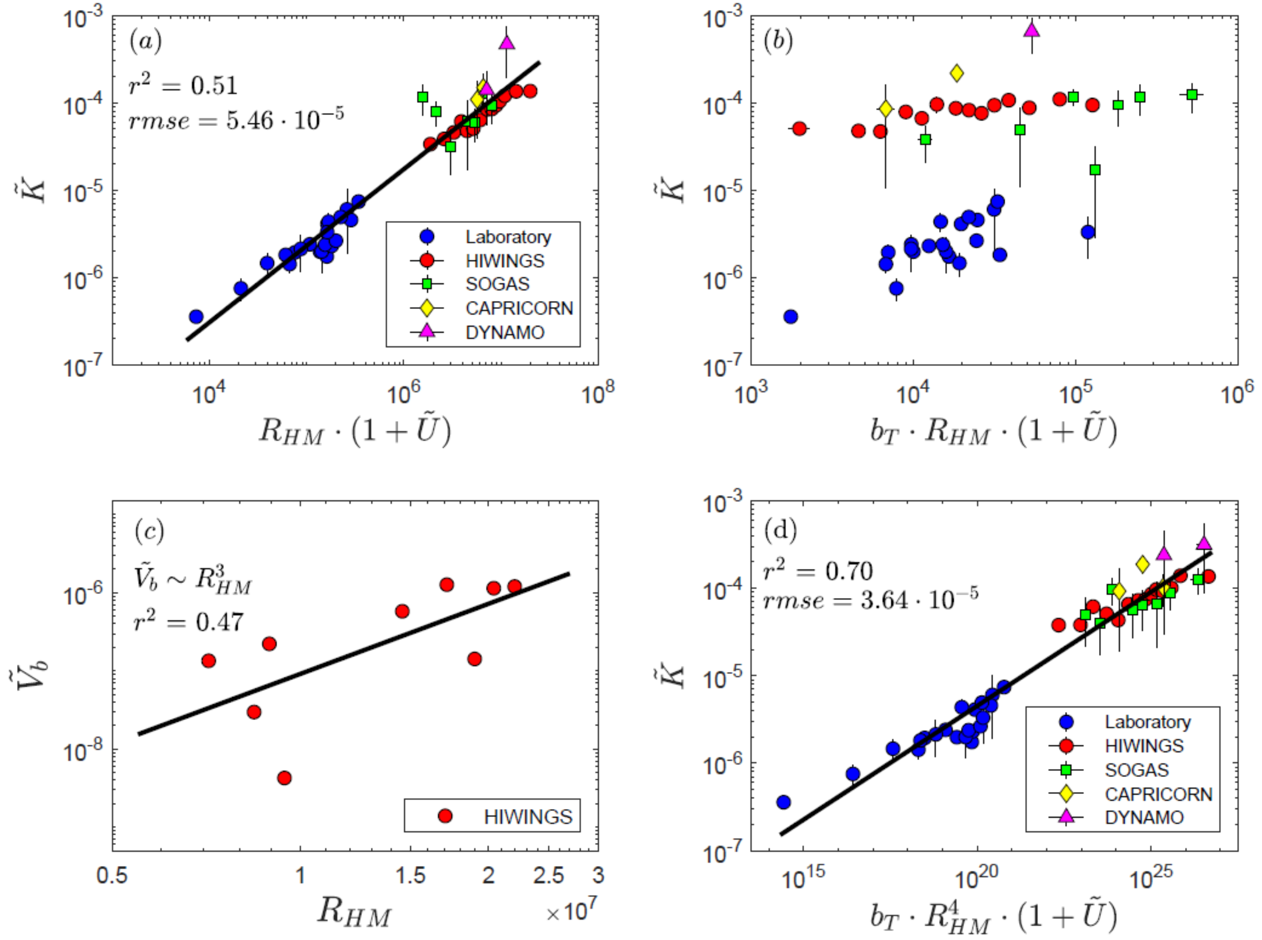
Field and Laboratory results

- Scaling

$$\widetilde{K} = \frac{K_{660}}{U_{wm}},\ R_{HM} = \frac{H_s \cdot U_{wm}}{\nu},$$

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

$\widetilde{K}$, nondimensional co_2 transfer velocity
R_{HM}, wave related Renolds Number
$\widetilde{U}$, nondimensional wind component
$\widetilde{V_b}$, nondimensional bubble injection rate
V_b, bubble injection rate (unit m/s)
K_{660}, corrected co_2 gas transfer velocity
b_T , wave breaking probability.
U_{wm}, wave orbital velocity, $= \pi H_s / T_{02}$
ν, water kinematic viscosity
U_*, wind friction velocity
H_s, significant wave height
g, gravitational acceleration



- Results

1. Formula $R_{HM} \cdot (1 + \widetilde{U})$ can collapse lab and field CO_2 transfer velocity
2. Dimensionless bubble injection rate is scaled with cubic R_{HM}. Then, this relationship is incorporated into the wave breaking (b_T) related formula
3. With implementation of bubble's effect, b_T related formula can collapse the results and have less error than that of $R_{HM} \cdot (1 + \widetilde{U})$

Parameterisation

A combined formula is proposed for breaking/non-breaking wave conditions which can be determined by spectral wave steepness ε (Babanin *et al* (2001))

$$\widetilde{K} = \begin{cases} 9.57 \cdot 10^{-11} \cdot \left[R_{HM} \cdot \left(1 + \widetilde{U}\right)\right]^{0.876}, & \varepsilon \leq 0.055 \\ 2.82 \cdot 10^{-11} \cdot \left[b_T \cdot R_{HM}^4 \cdot \left(1 + \widetilde{U}\right)\right]^{0.260}, & \varepsilon \geq 0.055 \end{cases}$$

Conclusions

1. Dimensionless parameterizations of CO_2 transfer velocity are established based on laboratory and field measurements

2. CO_2 transfer velocity is a function of wave and wave-breaking properties, with secondary dependence on the wind

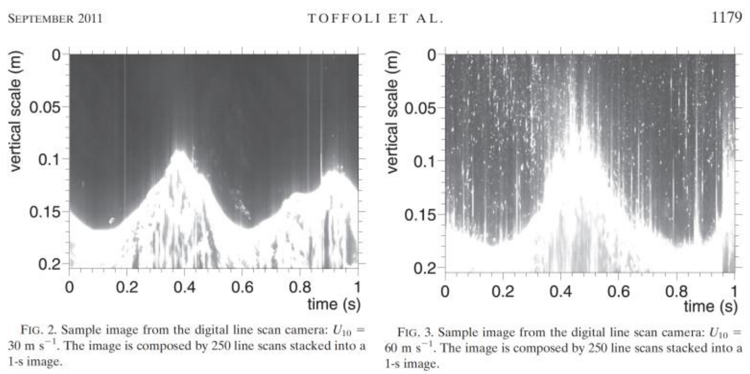
3. Bubble-related transfer is integrated in the formula when breaking is present, which reduces the scatter

Wave-Coupled spray productions — Definitions

Slides of Xingkun Xu

(Veron, 2015)

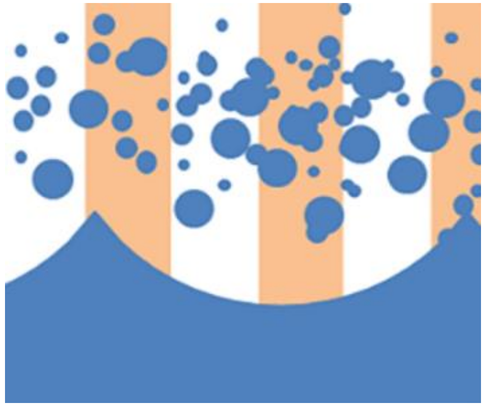
2. Methodology & Experiment in the Laboratory



$$I(z) = I_0 e^{-\mu \Delta z}$$ (Beer-Lambert law)

μ is the attenuation coefficient; Δz is the laser propagating distance

$$V(I) = -3 \times 10^{-10} I^2 + 5 \times 10^{-7} I - 8 \times 10^{-5}$$ (Toffoli et al. 2011 *JAOT*)



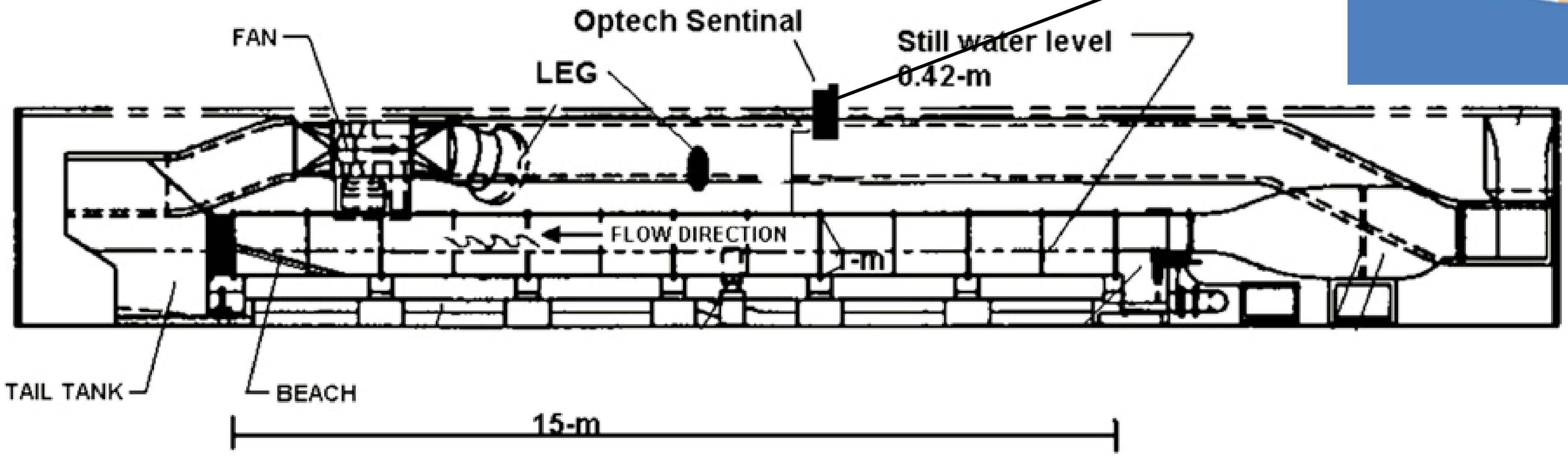
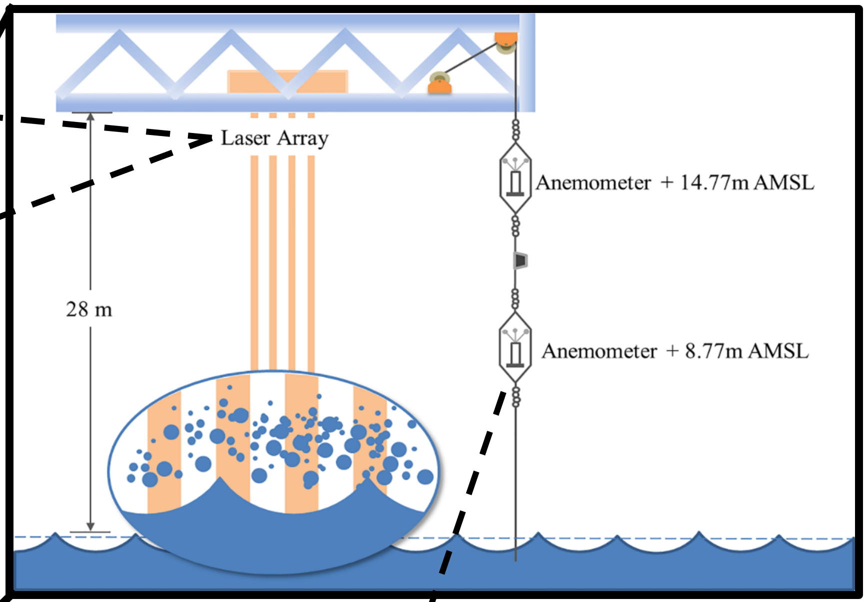


Fig. Schematic of experimental set up in the laboratory (University of Miami)

3. Observations in the Field

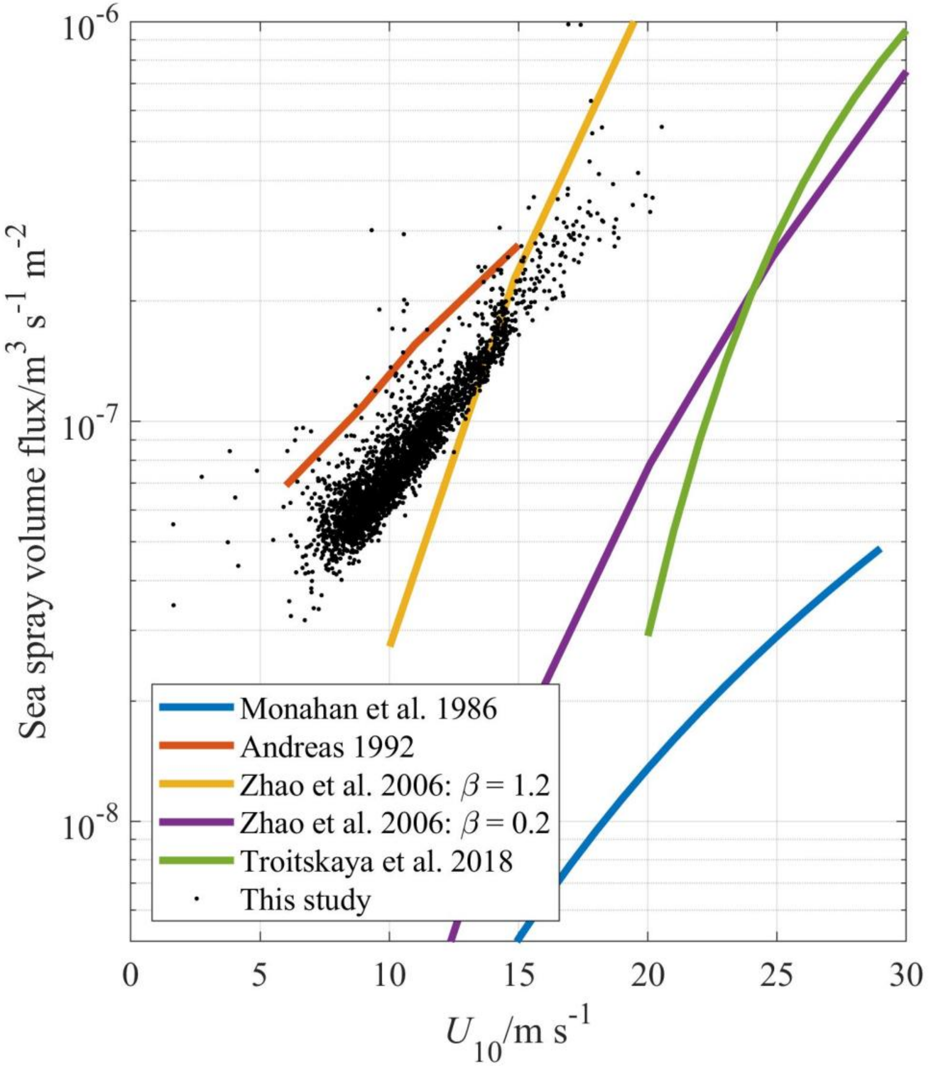
Laser range — Wave spectrum

laser attenuation — Spray volume flux

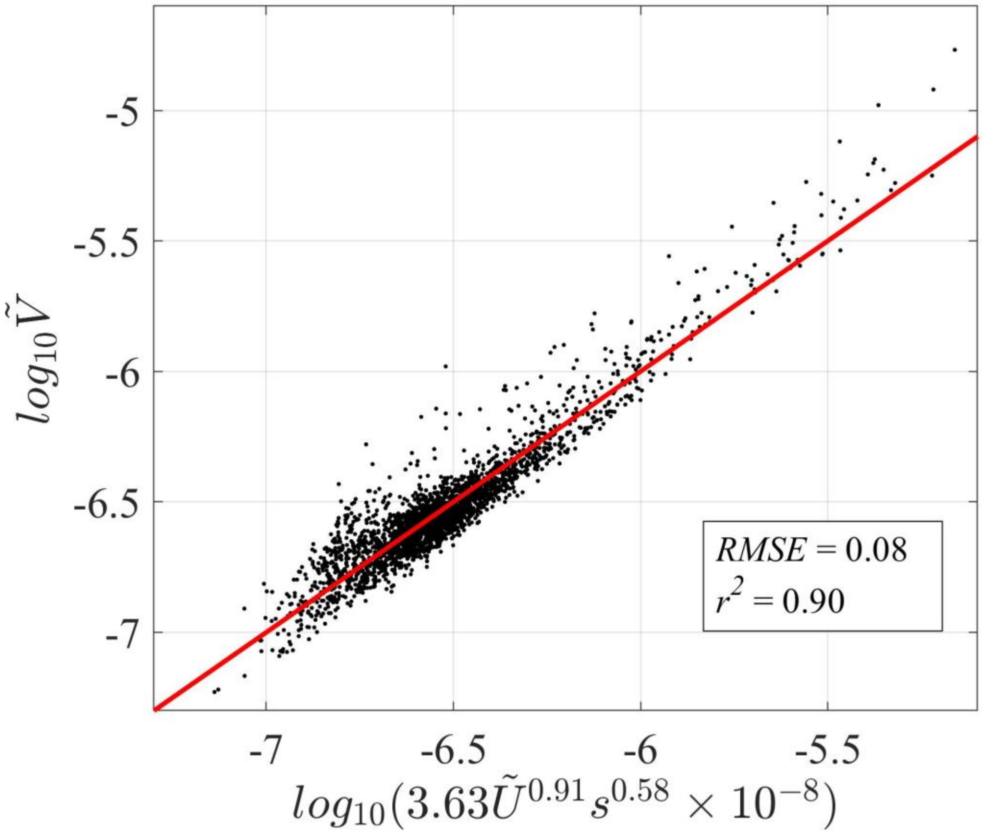


Data: Jan. - Oct. 2015 (Nov. and Dec. were missing, and TC Olwyn passing by in March)

3. Sea Spray Observations & Model



Xu, X et al. 2021 *JMSE*



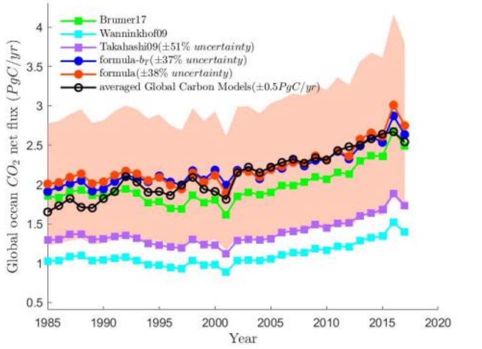
$$\tilde{V} = 3.63\tilde{U}^{0.91}s^{0.58} \times 10^{-8}$$

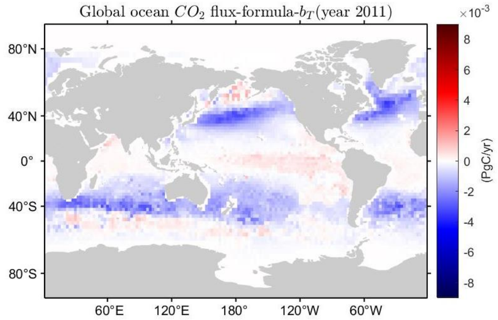
$$s = \frac{H_s k_m}{2} \qquad \tilde{U} = \frac{U_{10}}{U_*}$$

$$\tilde{V} \approx 1.99\tilde{U}\sqrt{s} \times 10^{-8}$$

Conclusions

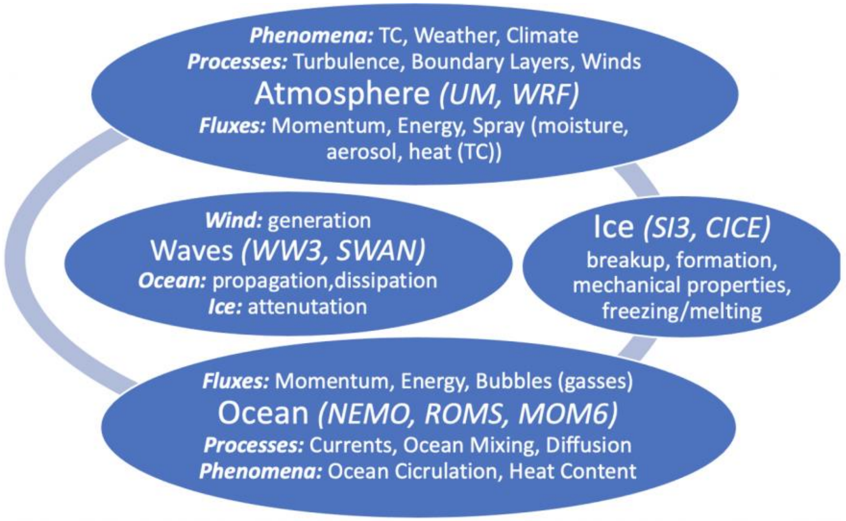
- coupling of small-scale models (waves, turbulence) with large-scale models (weather, climate) is necessary
  - physics is continuous
  - computing capabilities allow the coupling
- waves provide feedback and driving forcing
  - to the atmospheric boundary layer
  - to the upper ocean (usually overlooked)
  - to the large-scale air-sea interactions
- *waves are an essential contributor to the interface gas exchange and to spray production*
- wave climate also changes

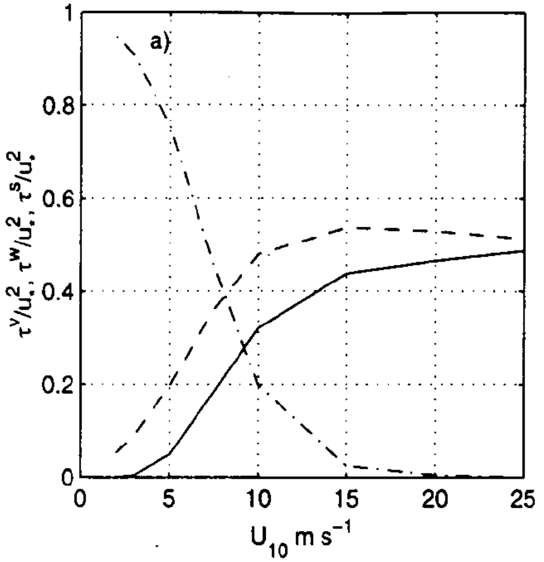




science of wave influences on large-scale processes at forecast scales

- two waves scales: wave crest and wavelength
- ***On the atmospheric side***:
  - waves form a separate boundary layer
  - waves inject spray/aerosol
- ***On the surface***
  - create or moderate all air-sea fluxes
  - different for light, moderate and extreme wind conditions
  - ***interact with ice***: breakup followed by melting away or refreezing/extending
- ***Below the surface***
  - momentum (currents), turbulence (mixing)
  - bubbles (gas exchange)
- ***Coastal, different wave dynamics***:
  - currents, mixing, sediment suspension and transport, erosion/accretion
  - wave setup

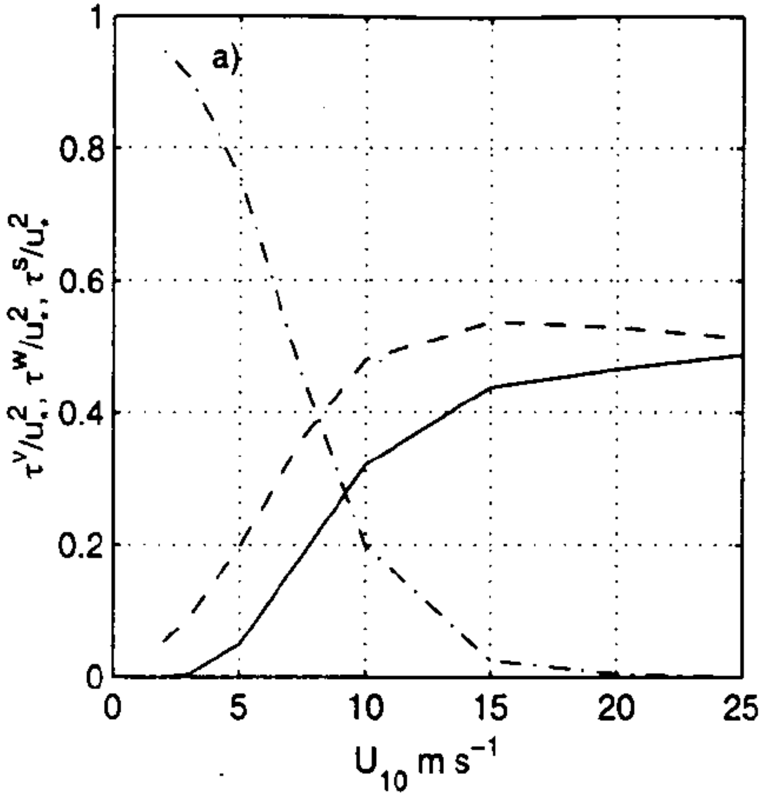




Kudryavtsev-Makin, 2011, BLM

Waves and currents influence on ABL

Momentum flux to currents and waves (through slope-coherent pressure and breaking)



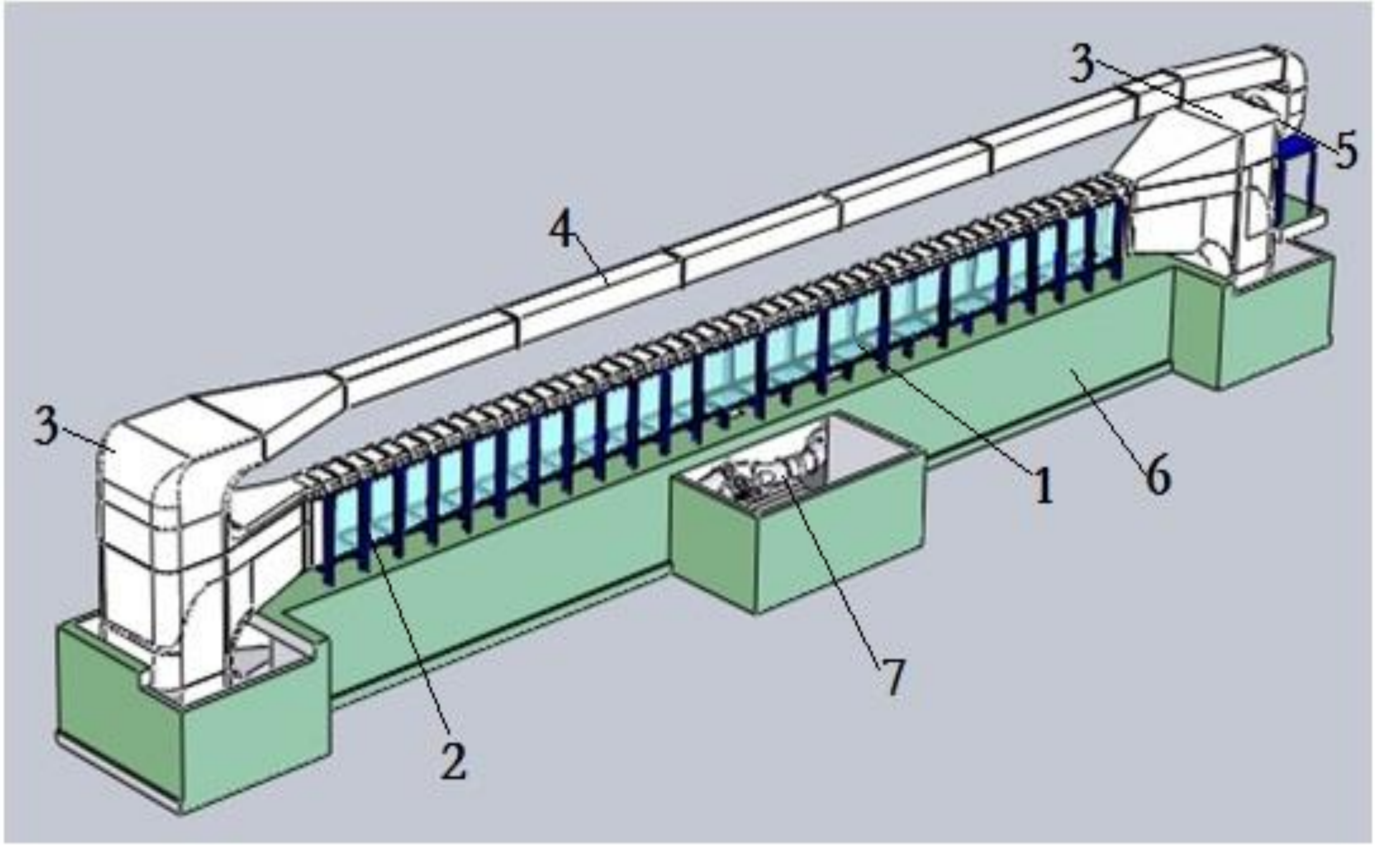
Kudryavtsev-Makin, 2011, BLM

Winds and waves change
Observations

- Both contributions are important
- At light winds momentum flux is dominated by currents
- At strong winds by waves
- Fluxes add up – total flux is constant
- Roughness lengths do not add up
- ABL models are based on roughness length – big problem when coupling with waves

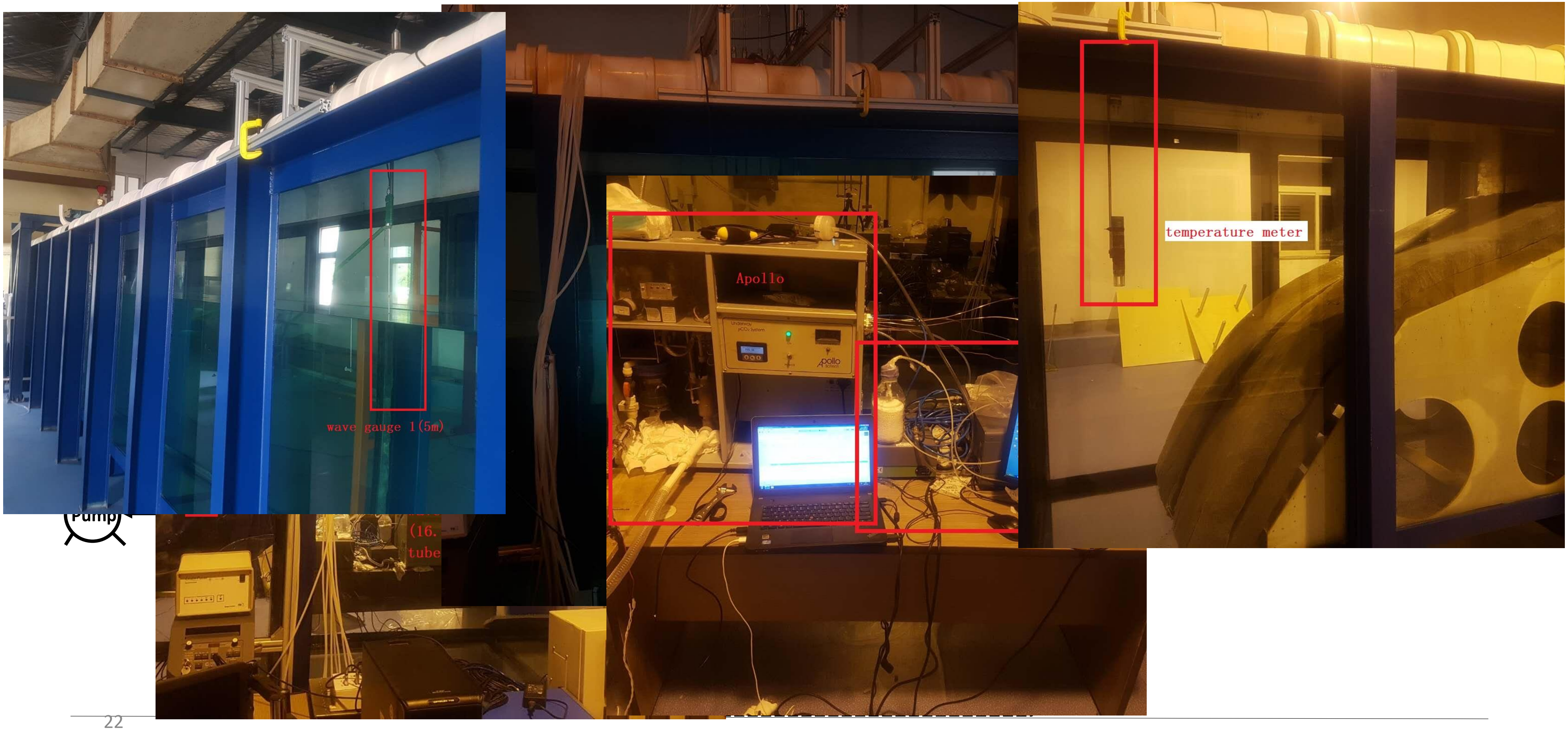
Laboratory Experiment - Wave Tank

- The wave tank is 45 m long, 1.8 m high, 1 m wide.
- The water depth is 1.2 m in experiments.
- The wave tank is equipped with a dissipation beach at one end and a piston mechanical wavemaker at the other end.
- The facility is in lab of First Institute of Oceanography, China.

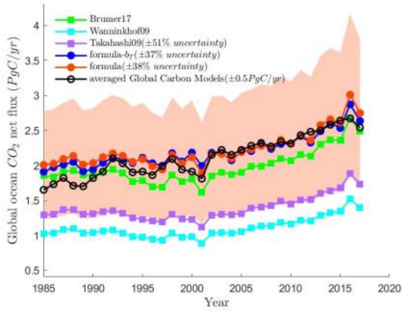


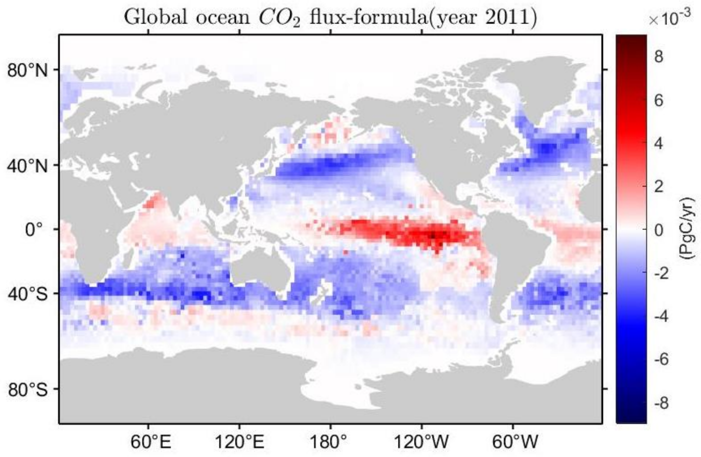
The diagram of the wave tank. 1-Glasses; 2-Wavemaker; 3- Plenum chamber; 4-Wind channel; 5-Fan; 6-Tank foundation; 7-Water channel.

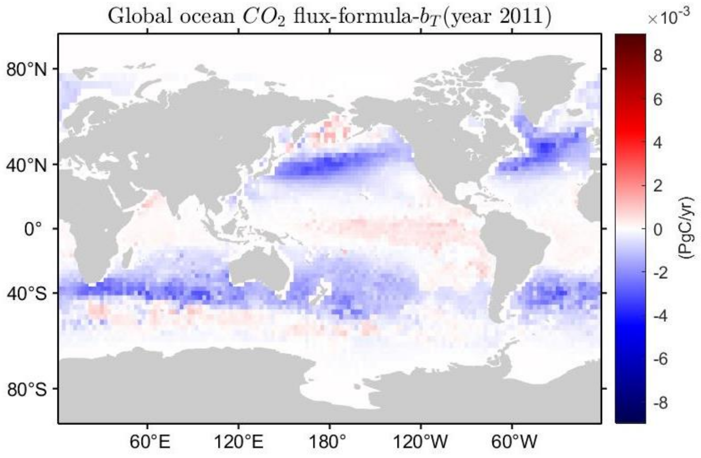
Laboratory Experiment - Setup

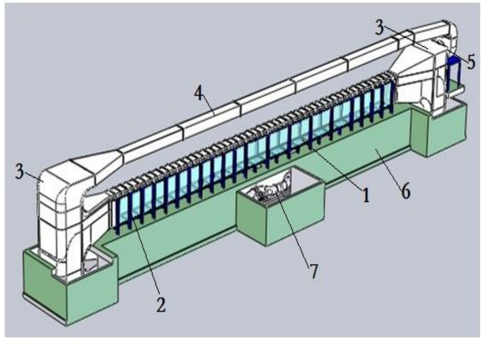


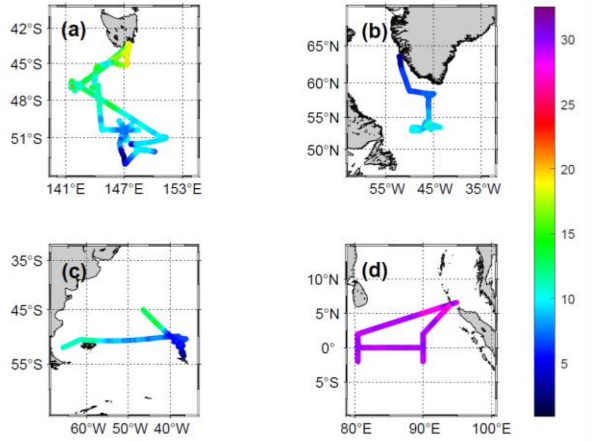
Ocean interface. CO_2 exchange











	Parameterization
Takahashi 2009	$k_{660} = 0.26 \cdot U_{10}^2 \cdot (660/Sc)^{0.5}$
Wanninkhof 2009	$k_{CO_2} = 3 + 0.1 \cdot U_{10} + 0.064 \cdot U_{10}^2 + 0.011 \cdot U_{10}^3$
Brumer 2017 (1)	$k_{CO_2} = 2.04 \cdot 10^{-4} \cdot {R_{aw}}^{0.88}$, $R_{aw} = U_* \cdot H_s / \nu$
formula	$\widetilde{K} = \frac{K_{CO_2}}{U_{wm}} = 7.2 \cdot 10^{-11} \cdot \left(R_M \cdot (1 + \widetilde{U})\right)^{0.9}$ $R_M = \frac{H_s \cdot U_{wm}}{\upsilon}, \widetilde{U} = \frac{U_*}{\sqrt{g \cdot h_s}}$
Formula-b_T	$\widetilde{K} = \frac{K_{CO_2}}{U_{wm}} = 2.6 \cdot 10^{-11} \cdot \left(b_T \cdot R_M^4 \cdot (1 + \widetilde{U})\right)^{0.26}$

slide of Shuo Li

3. Observations in the Field — Limitation

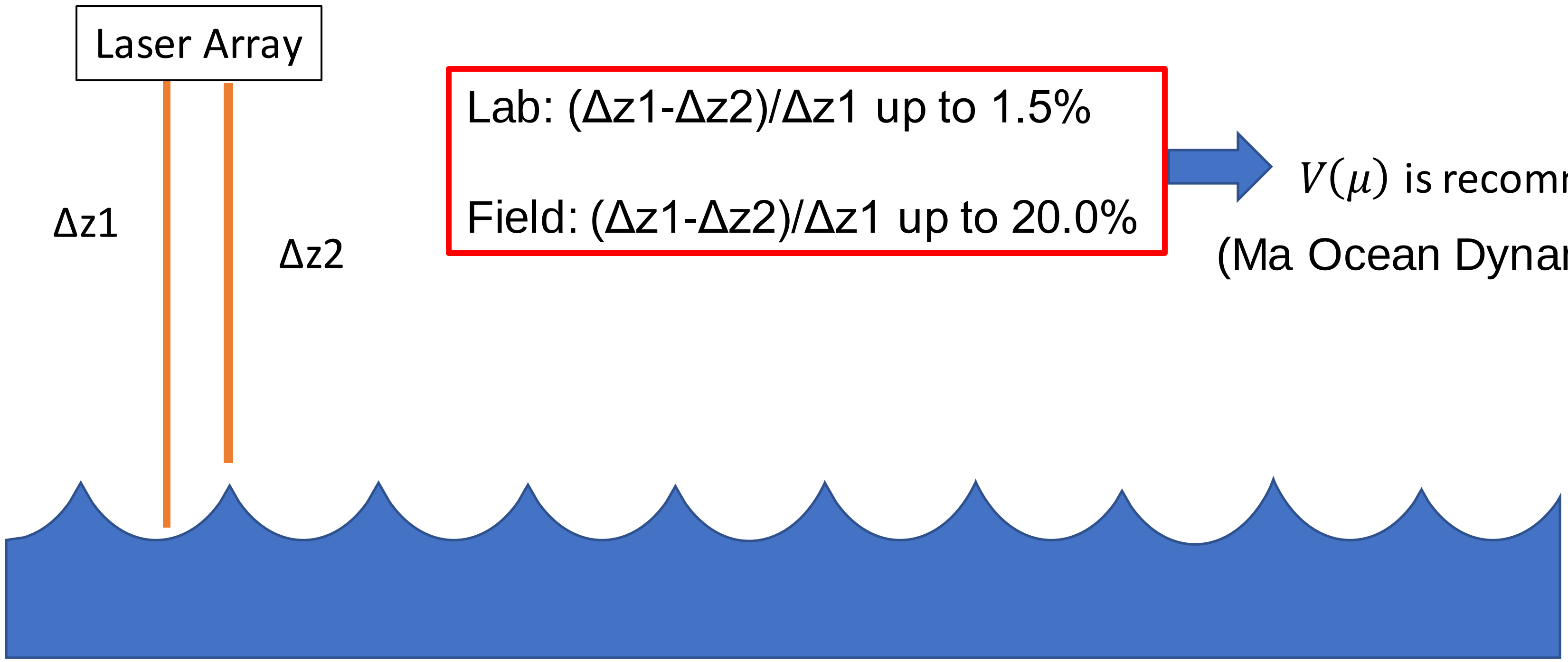
$V(I) = -3 \times 10^{-10} I^2 + 5 \times 10^{-7} I - 8 \times 10^{-5}$

(Toffoli et al. 2011 JAOT)

Can't be applied in the field!

$I(z) = I_0 e^{-\mu \Delta z}$ (Beer-Lambert law)

μ is the attenuation coefficient; Δz is the laser propagating distance



Lab: (Δz1-Δz2)/Δz1 up to 1.5%

Field: (Δz1-Δz2)/Δz1 up to 20.0%

$V(\mu)$ is recommended

(Ma Ocean Dynamics 2020)

3. Observations in the Field — Quality Control

1. Introduce the variety of Δz (two times of laser range). Previously, it is a constant (Ma 2020 Ocean Dynamics).
2. Calibrate raw data by excluding laser partial dropping out and saturation errors.
3. Exclude less accurate laser readings.
4. Revised the winds following Curcic, M., & Haus, B. K. (2020): "Revised estimates of ocean surface drag in strong winds. *Geophysical Research Letters*"

3. Observations in the Field — Quality Control

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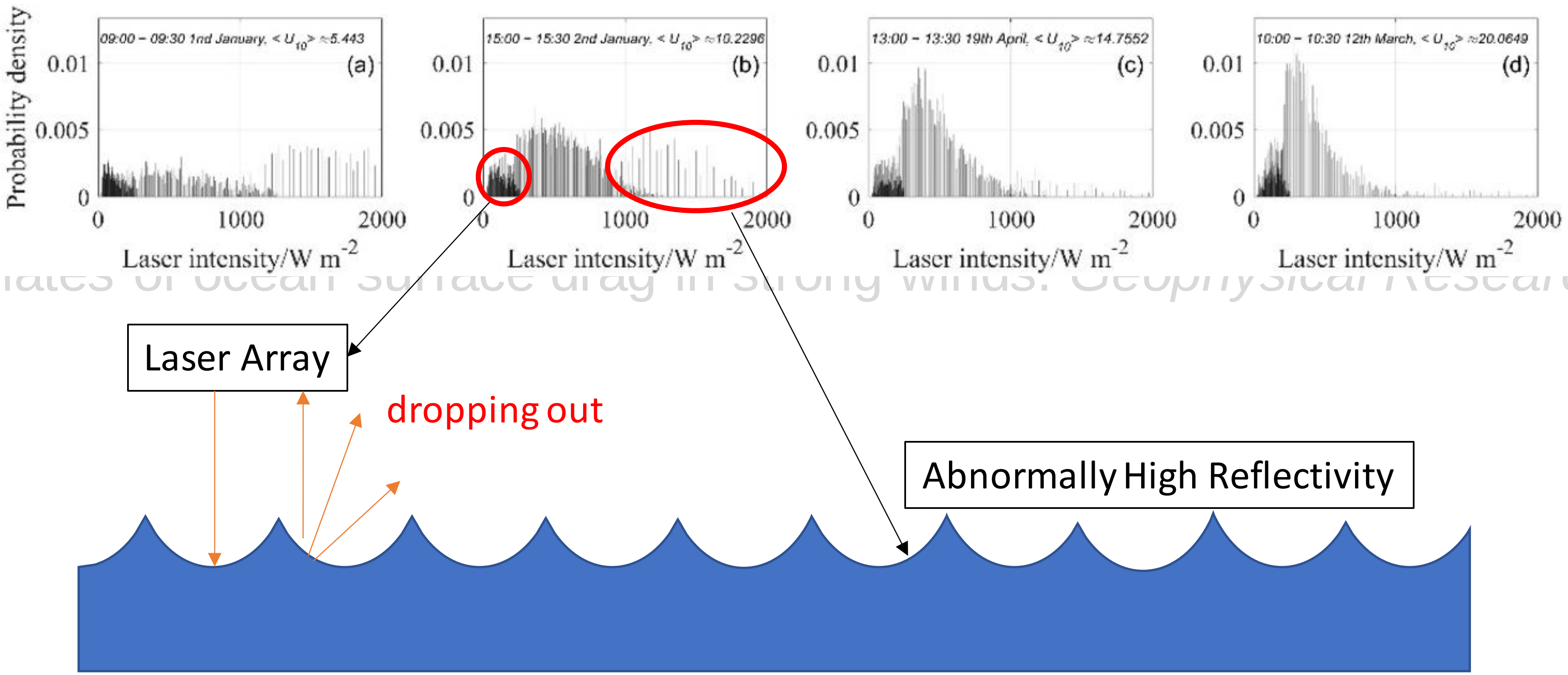
3. Excl

4. Rev … “Revised esti… Letters”



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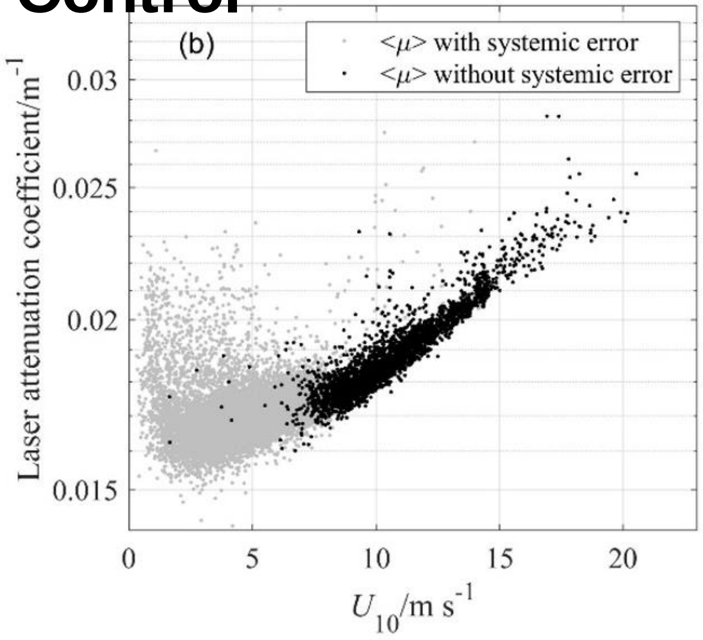

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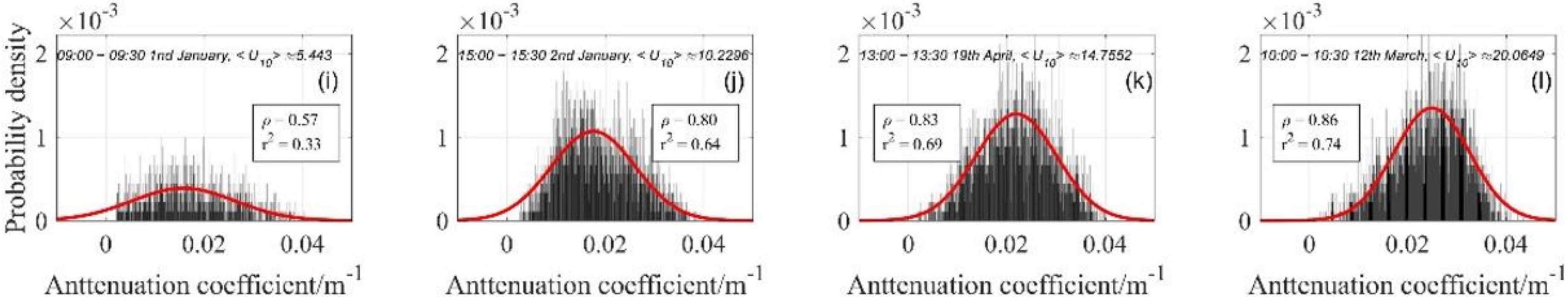
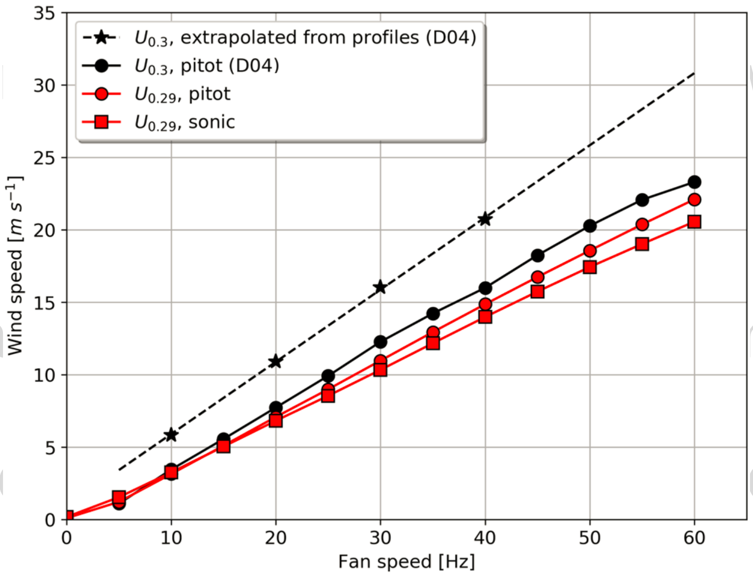
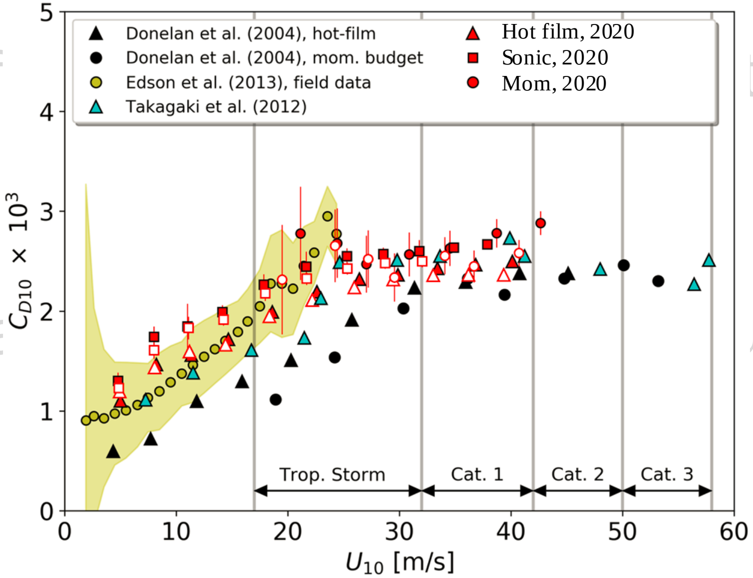


Still, motionless liquid with a few waves or ripples would cause less accurate laser readings (Laser User Manual), which could lead to abnormal laser attenuation coefficient.

3. Observations in the Field — Quality Control

1. Int… …wo times of… …t is a constant (M…

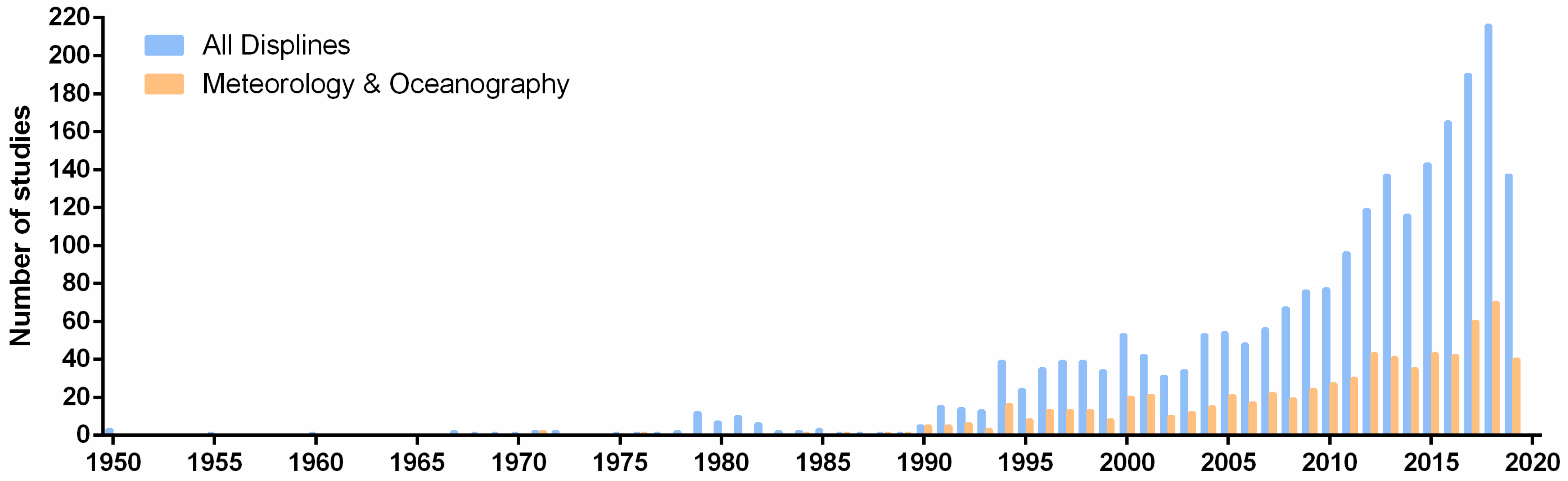




2. Ca… …ng laser pa… …ration errors.
3. Ex… …eadings.
4. Revised the winds following Curcic, M., & Haus, B. K. (2020): "Revised estimates of ocean surface drag in strong winds. *Geophysical Research Letters*"

1. Basic Introduction — Studies

Search “sea spray/ocean spray” from Web of Science database, we can get (since 1950s):



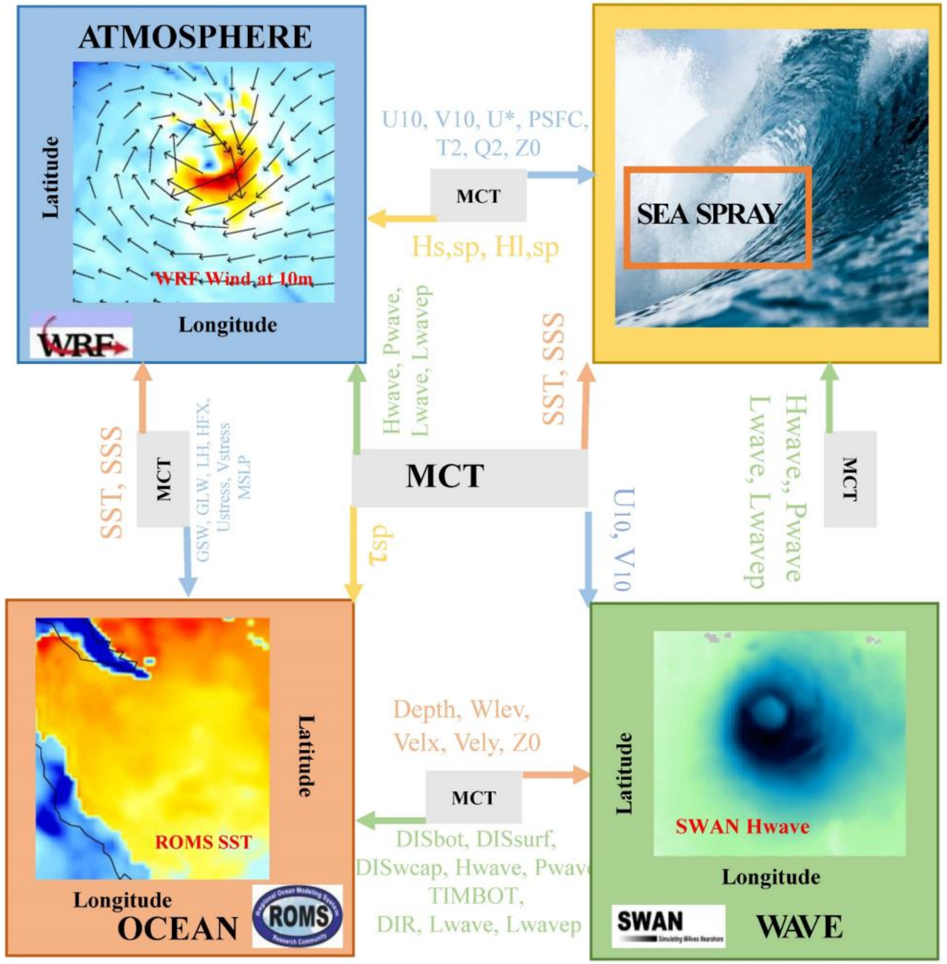
Importance:

- **Sea salt aerosols; Air pollution; Gas exchange** (Textor C. et al. 2006 *Atmos. Chem. Phys;* Allison Staniec et al. 2021 *Nature Geoscience*).
- **Air-sea momentum fluxes; Sensible and latent heat fluxes exchanged** (Andreas E.L. 1992 *JPO;* Fairall C.W. 1994 *Global Atmos. Ocean Syst.*).
- **Tropical Cyclone intensity** (Bao J.W. *2011 Mon. Weather Rev.;* Bin L. 2011 *Mon. Weather Rev.*)**.**

Questions:

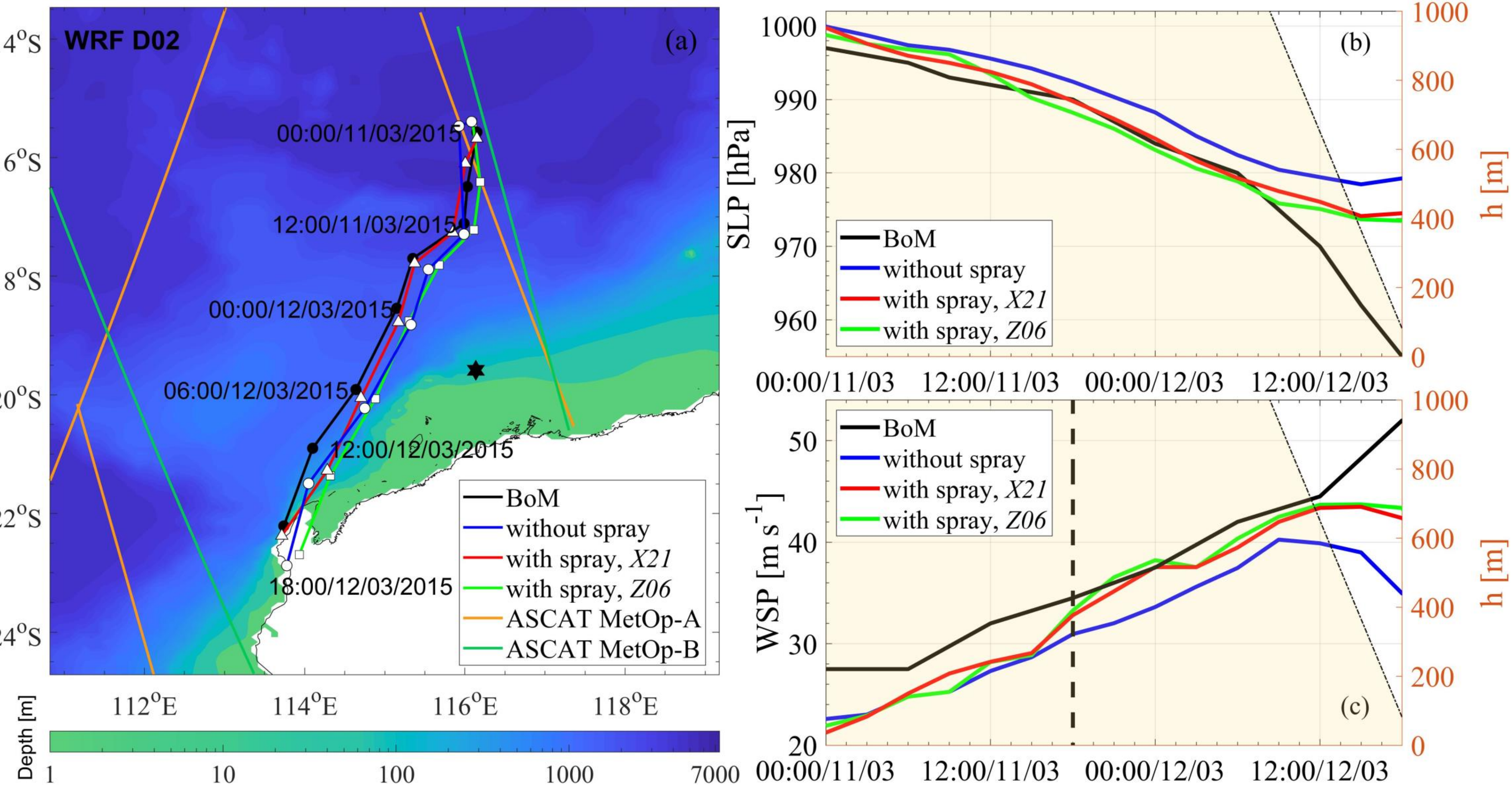
- At higher wind speeds, **measurements** are scarce.
- How the sea spray affects **momentum** and **enthalpy fluxes** are not yet well resolved.
- **Wave** properties need to be considered?
- **Single parameter alone (i.e., wind)** in sea spray production parameterizations.

1. Atmosphere-Ocean-Wave Coupled Model

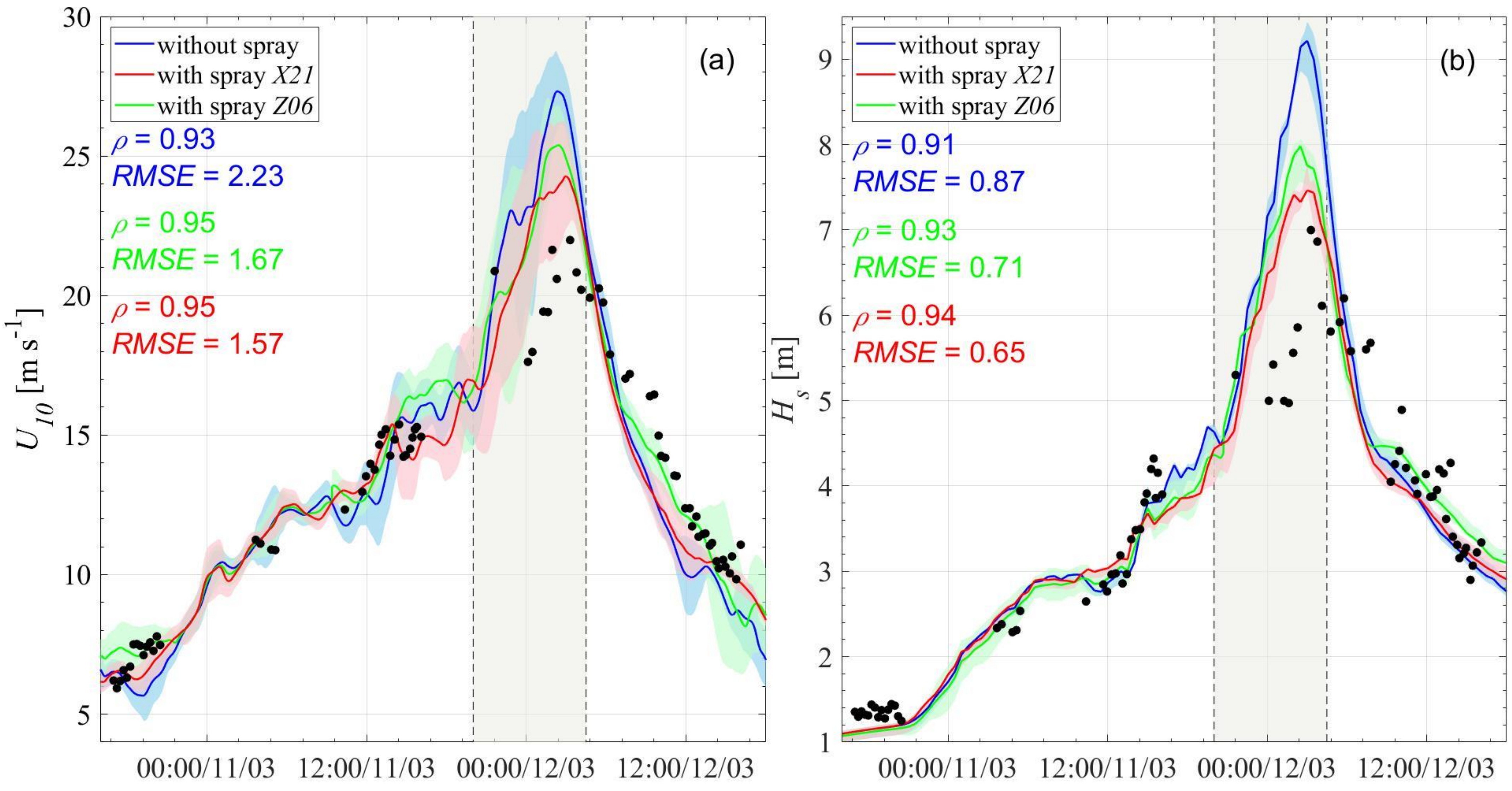


Variables	**Description**
GSW, GLW $[W \cdot m^2]$	Surface short, and long wave radiation
LH, HFX $[W \cdot m^{-2}]$	Surface latent, and sensible heat fluxes
Ustress, Vstress $[N \cdot m^{-2}]$	Surface U- and V- wind stress
MSLP $[Pa]$	Mean sea level pressure
SST $[°C]$	Sea surface temperature
U10, V10 $[m \cdot s^{-1}]$	U- and V- wind speed at 10 meter
U* $[m \cdot s^{-1}]$	Friction velocity
T2 $[°C]$	Surface 2-m air temperature
Q2 $[kg \cdot kg^{-1}]$	Water vapor mixing ratio at 2 meter
Z0 $[m]$	The roughness length
Hs,sp, HL,sp $[W \cdot m^{-2}]$	Sea spray induced sensible and latent heat fluxes
DISbot, DISsurf, DISwcap $[W \cdot m^{-2}]$	Energy dissipation due to bottom friction, surf-breaking and white-capping
Hwave $[m]$	Significant wave height
Pwave $[s]$	Peak wave period
TIMBOT $[s]$	Bottom wave period
DIR $[°]$	Wave direction
Lwave, Lwavep $[m]$	Mean and peak wavelength
Depth, Wlev $[m]$	Water depth and water level
Velx, Vely $[m \cdot s^{-1}]$	U- and V- current velocity

2. Model Domain & Simulated SLP and WSP



3. Validate by Buoy Data



4. Sea Spray Induced Heat and Momentum Fluxes