15th CAS-TWAS-WMO Forum
15th AeroCom / 4th AeroSAT workshops on Atmospheric Aerosol, Beijing,2016

# The transport of sea-spray spume during high-wind conditions and its effects on sea salt aerosol emissions

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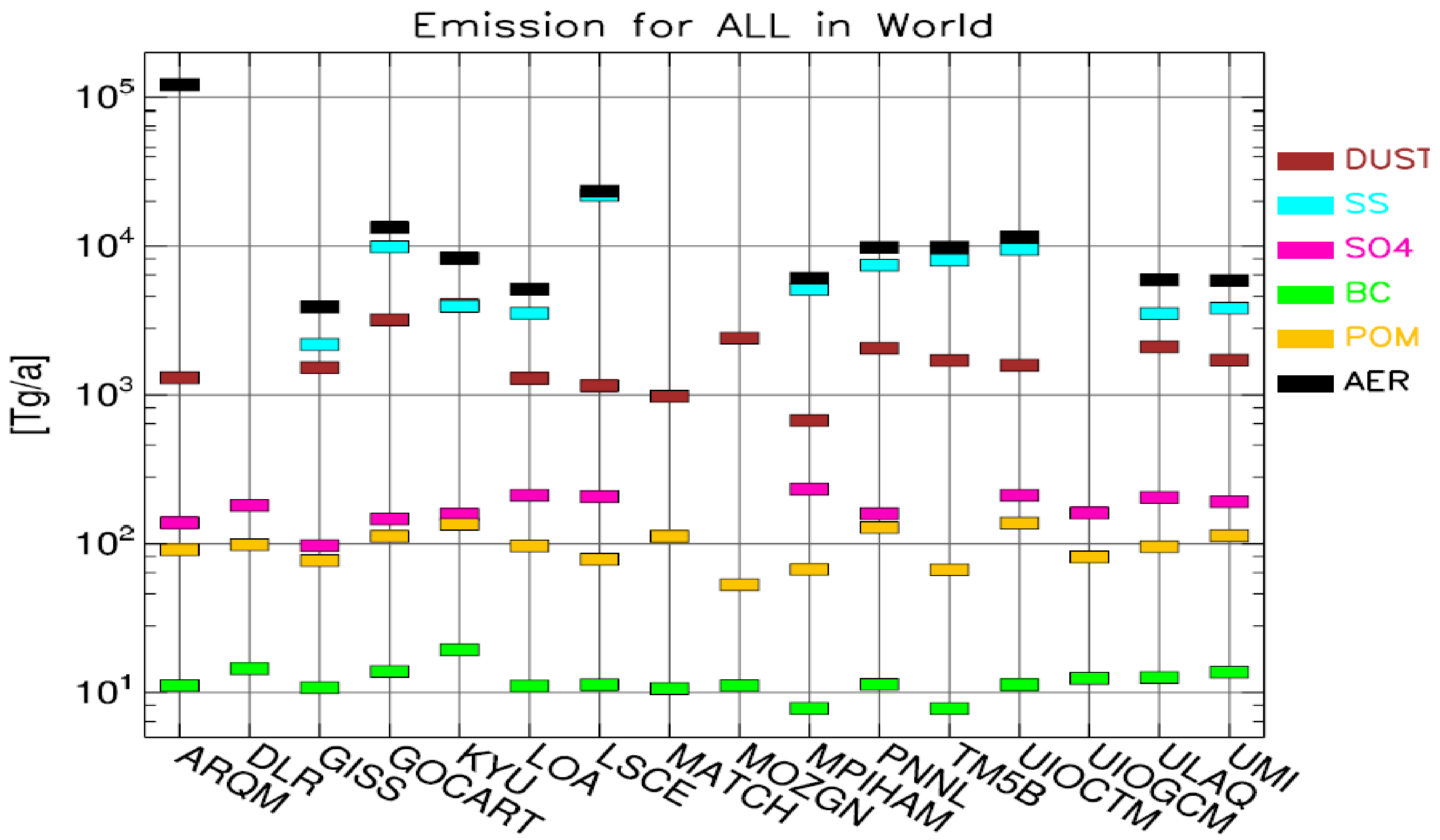
# Background

Ocean-produced sea-salt aerosols are the most numerous naturally emitted aerosols.

**Effects**:

- Air quality and visibility of the coastal cities
- Direct and indirect climate effects
- Related with the salinity upper boundary layer in the Ocean Generation Circulation Model (OGCM), the small quantity perturbation of salt flux can modify the ocean's meridional circulation (*Bryan*, 1986; *Marotzke et al*. 1988, 1991; *Weaver*, 1991; *Hofmann and Rahmstorf*, 2009)



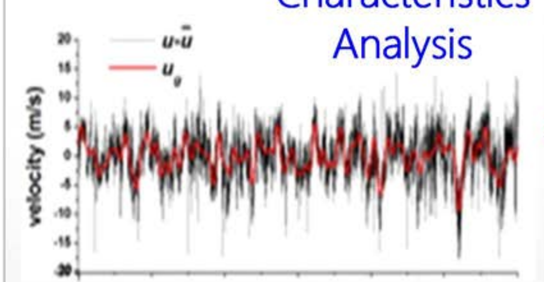

（*Textor et al.*, 2006, Analysis and quantification of the diversities of aerosol life cycles within AeroCom, ACP）

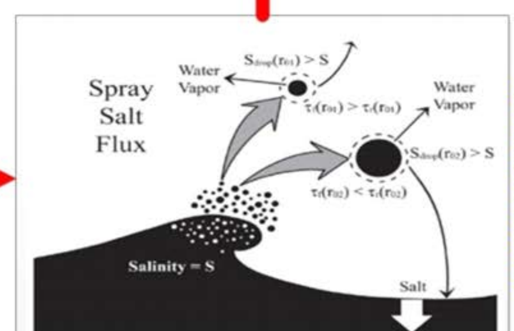
# What we do?

**Goals:**
- Parameterization
- Model Support

Observations

Characteristics Analysis



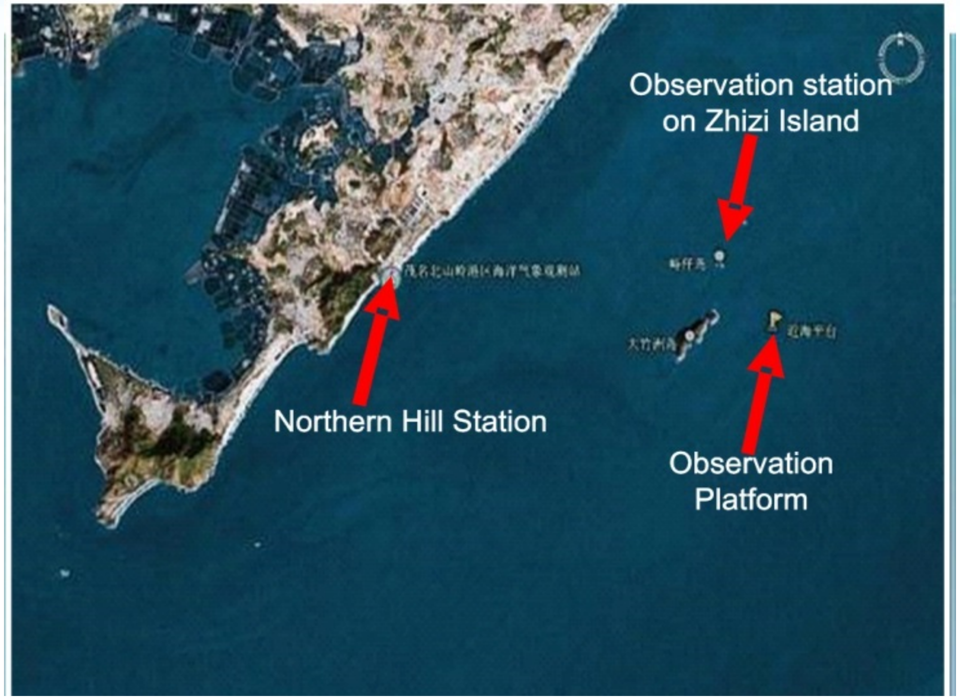




Mechanism & Simulations

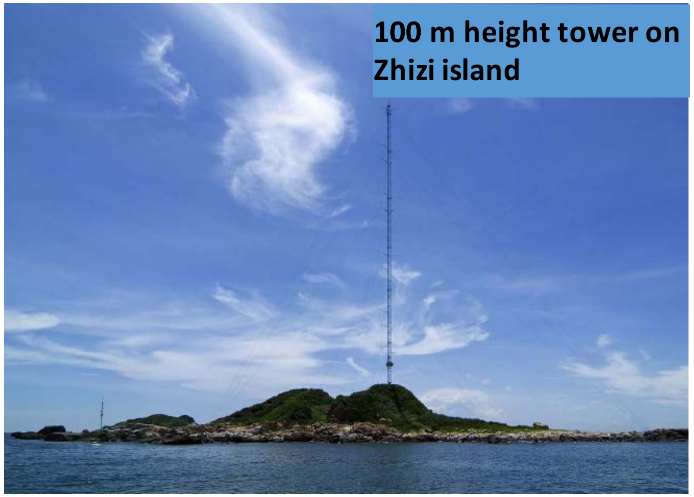
# Outline

1. Atmospheric Boundary Layer (ABL) observations and analysis
2. Methodology
3. Results
4. Conclusions

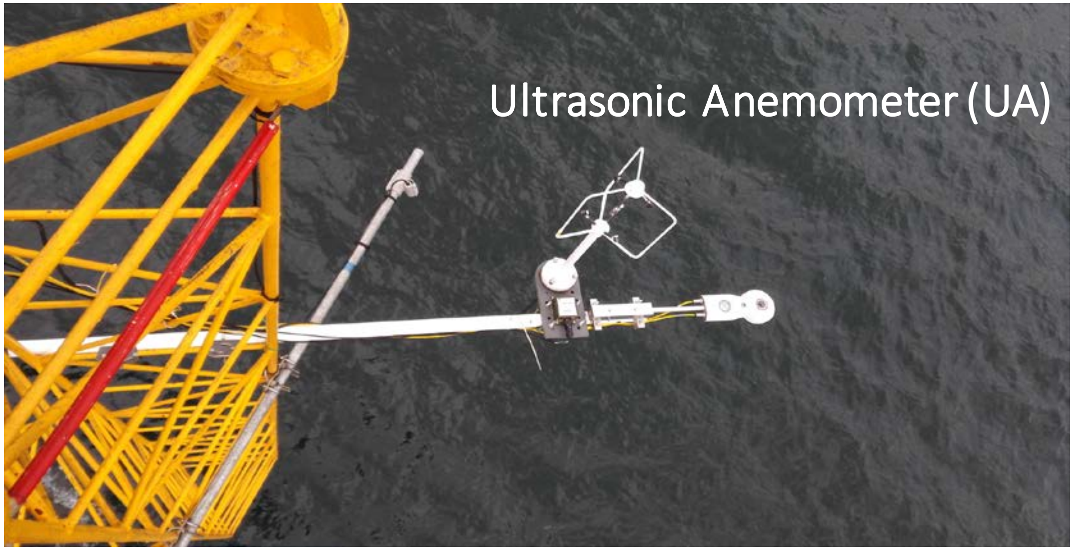
# 1. ABL Observations and analysis




Marine Meteorological Science Experiment Base
(Bohe, Guangdong, China)

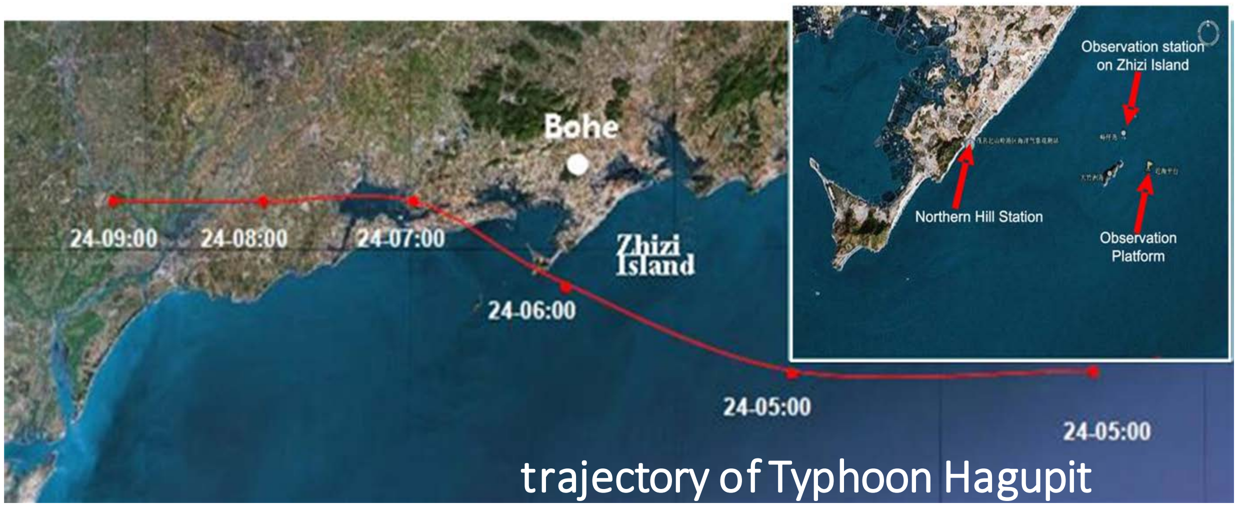



# Instruments settled on the platform



# Two typical cases

- Typhoon: Hagupit, September 2008, data from Zhizi island & observation platform;



trajectory of Typhoon Hagupit

10-min average: 48 m/s;
3-sec instant: 64 m/s

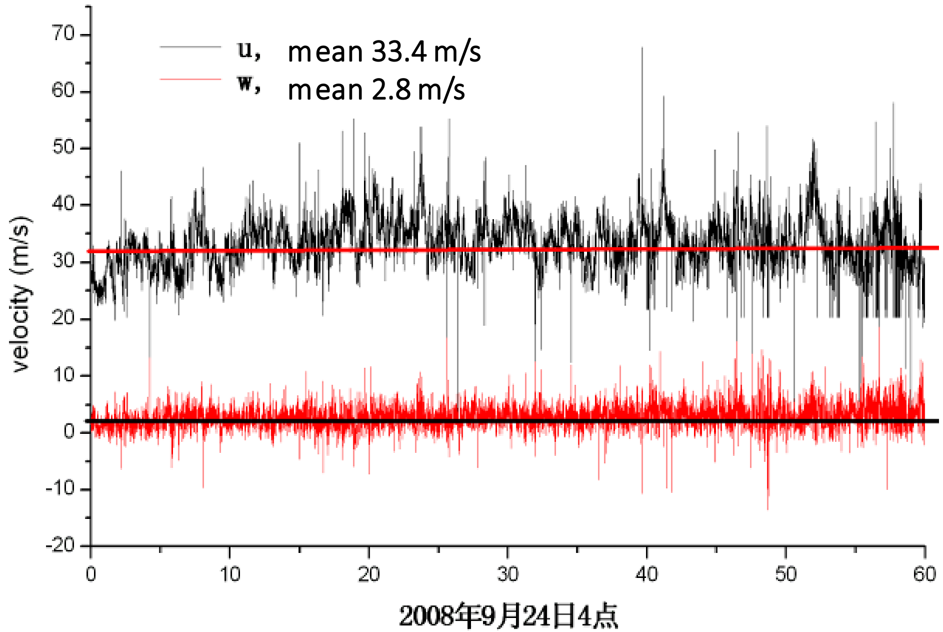
- Cold surge: Jan.-May 2012, data from Observation platform;

289 hours: 10 m/s; 103 hours: 12 m/s

Observations are continued...

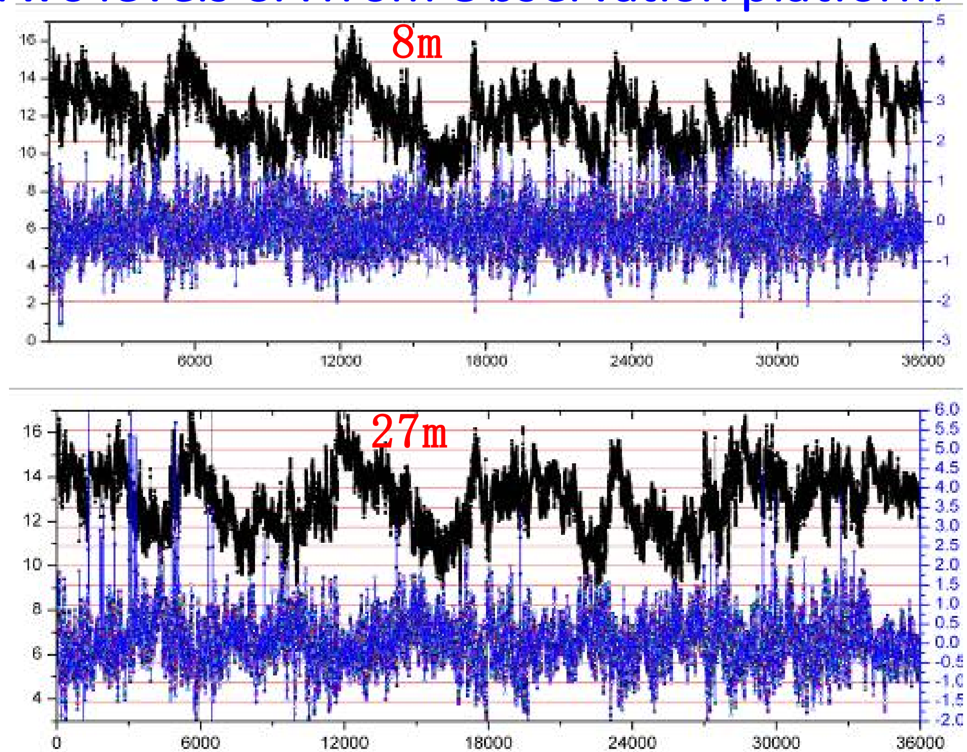
# ABL characteristics analysis

Hagupit:
60 m UA from Zhizi tower




Time series of *u* and *w* during
0400–0500 BST 24 September 2008

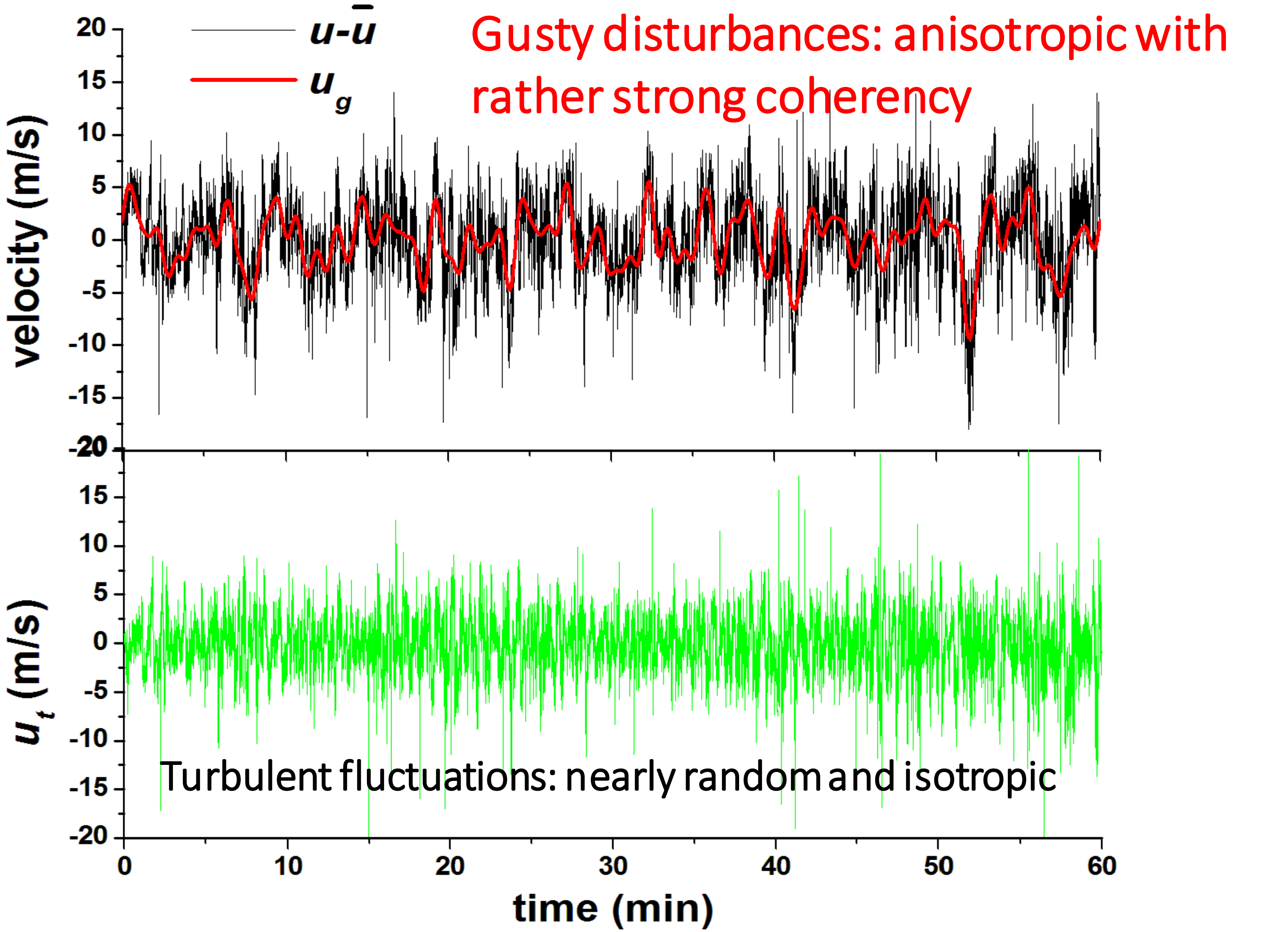
Cold surge:
Two levels UA from Observation platform

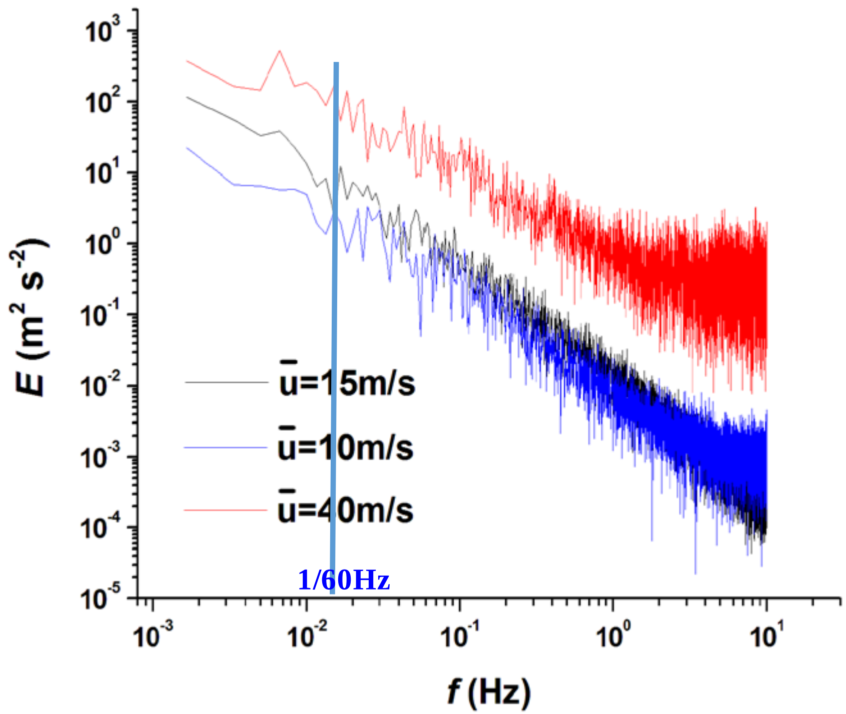



Time series of *u* and *w* during
2100–2130 BST 23 March 2012

**C1:** ABL near the sea surface is not the classical Kolmogorov turbulence, not completely random or isotropic.

# C1: there exists coherent gusty disturbances

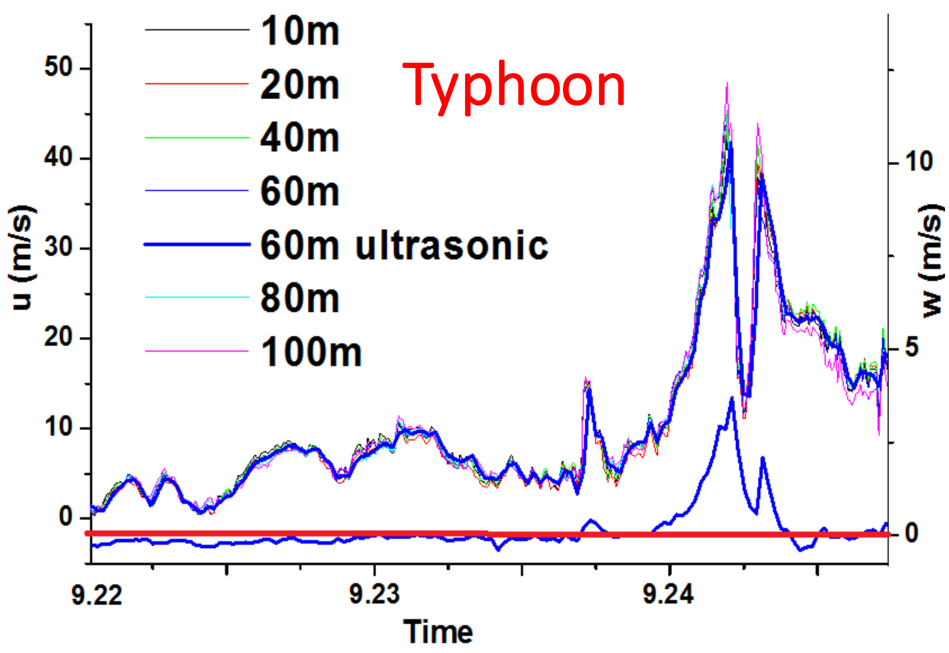


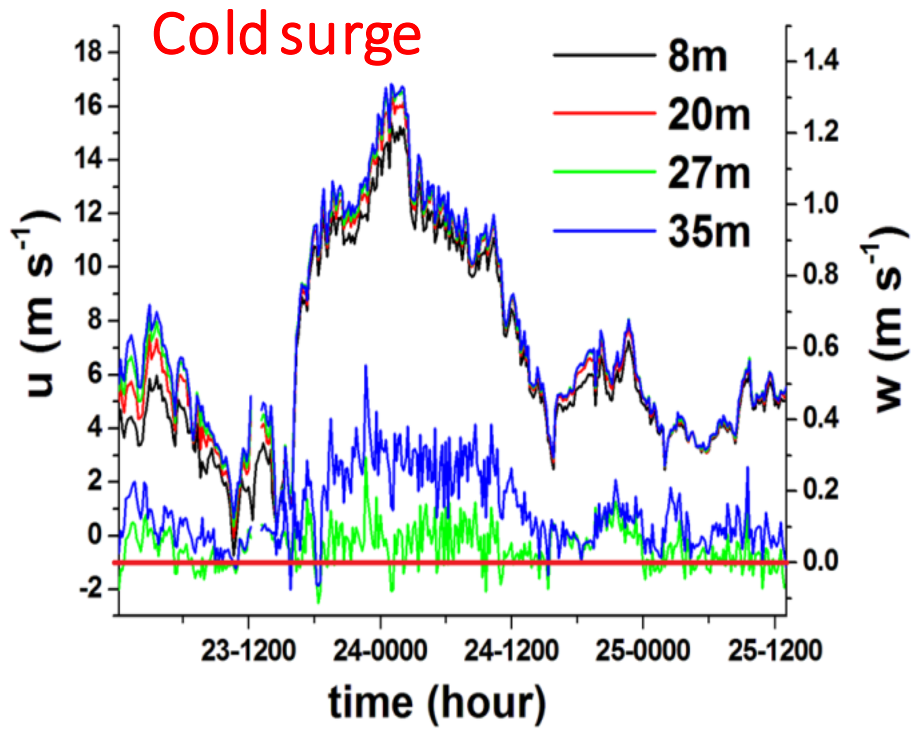



energy spectrum of the high-frequency turbulences
at different wind speeds
(black: cold surge; blue & red: Hagupit)

**C2:** The energy spectrum of the high-frequency turbulences still follow the Kolmogorov's law

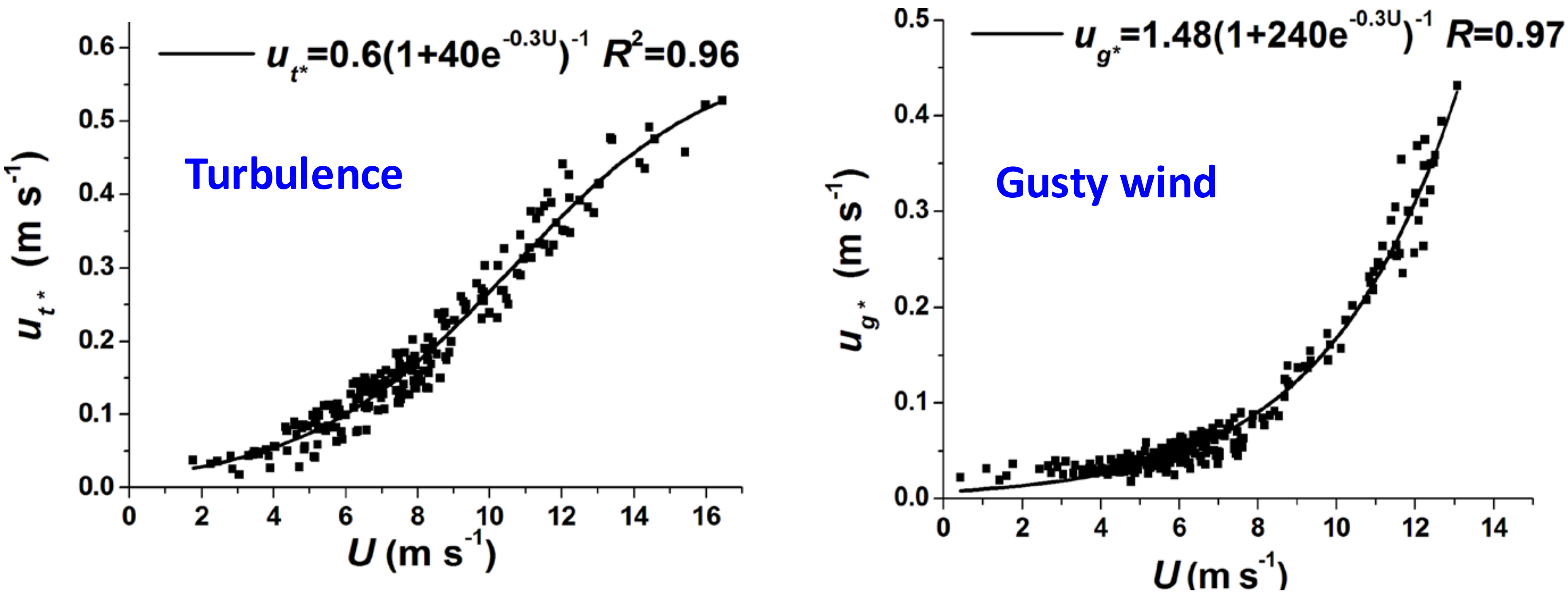
# Time series of the *u* and *w* profiles




**C3:** the 10-min average horizontal wind speed *u* is almost independent of height

# C4: *u* can be an important factor in parameterization




Parameterization of friction velocity

# 2. Method of the transport of particles in high-wind ABL

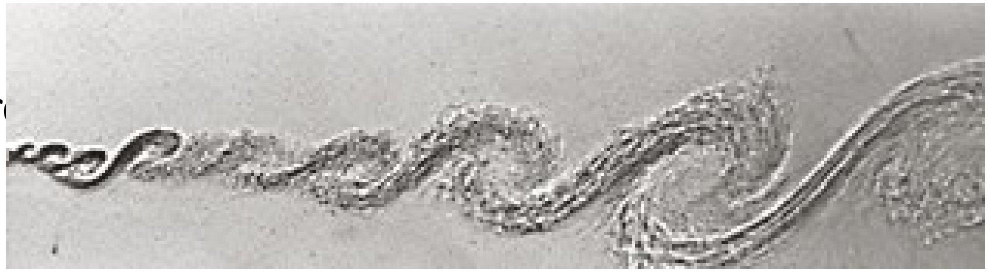
## Why consider coherent gusty wind?

ABL: turbulence

Werner Heisenberg : "When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."

Two progresses： intermittency & coherent structure

Brown-Roshko structure in the mixing layer



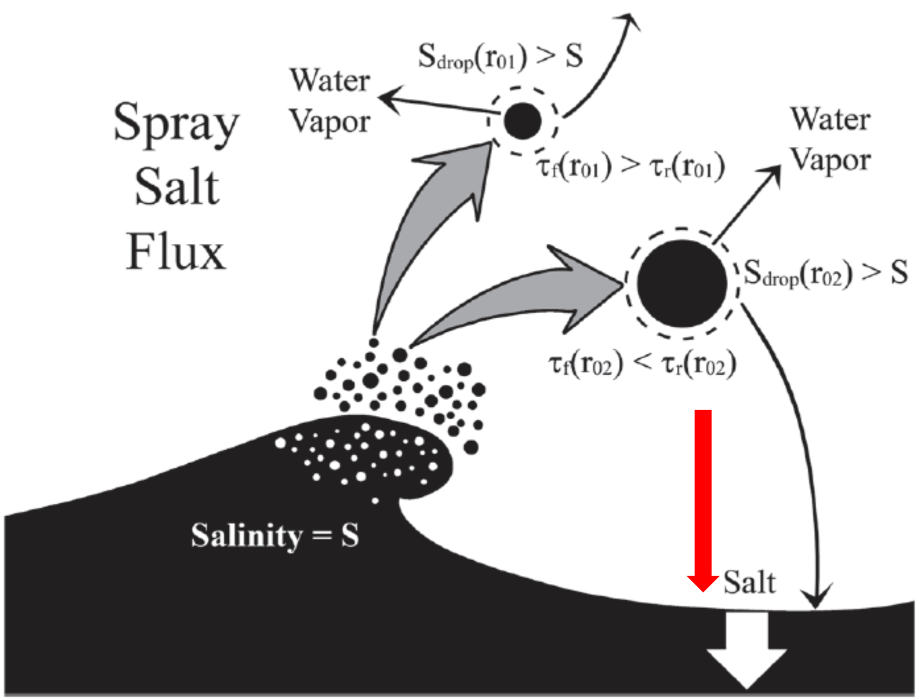
(Coherent structure in ABL? Complex underlying surface)

Coherent structures are important to the maintenance and evolution of turbulence, and also to the particle & energy transport.

# The current transport method of the sea-spray droplets

is based on the classical turbulence theory

- Sea salt aerosols are usually less than 20 µm;
- The large size droplets would fall back into the ocean relatively quickly in the absence of wind.




The large size (>20 µm) spume?

However, the large size spume are usually generated because of the high-wind.

Veron (2015): *Annu. Rev. Fluid Mech.*

- Transport & effects of large size spume are still in debate;
- The current schemes are not suitable for strong wind

# The modified method is based on the new characteristics of ABL in high-wind:

$$\boldsymbol{u} = \overline{\boldsymbol{u}} + \boldsymbol{u}'$$

$$\parallel$$

$\boldsymbol{u_t}$: makes particle diffuse

+

$\boldsymbol{u_g}$: cause "mini-scale" advection

Transport in high-wind conditions

# Vertical transport of the spume considering gusty wind

## Modified Lagrangian stochastic model

$$\begin{cases} \dfrac{\mathrm{d}u_p(t)}{\mathrm{d}t} = \dfrac{f}{\tau_p}\left(\bar{u}\left(x_p, z_p, t\right) + u_g\left(x_p, z_p, t\right) - u_p\left(x_p, z_p, t\right)\right) \\ \dfrac{\mathrm{d}w_p(t)}{\mathrm{d}t} = \dfrac{f}{\tau_p}\left(\bar{w}\left(x_p, z_p, t\right) + w_g\left(x_p, z_p, t\right) + w_t\left(x_p, z_p, t\right) - w_p\left(x_p, z_p, t\right)\right) - g \end{cases}$$

$$\begin{cases} \dfrac{\mathrm{d}x_p}{\mathrm{d}t} = u_p \\ \dfrac{\mathrm{d}z_p}{\mathrm{d}t} = w_p \end{cases}$$

Blue： from the observation data & parameterization

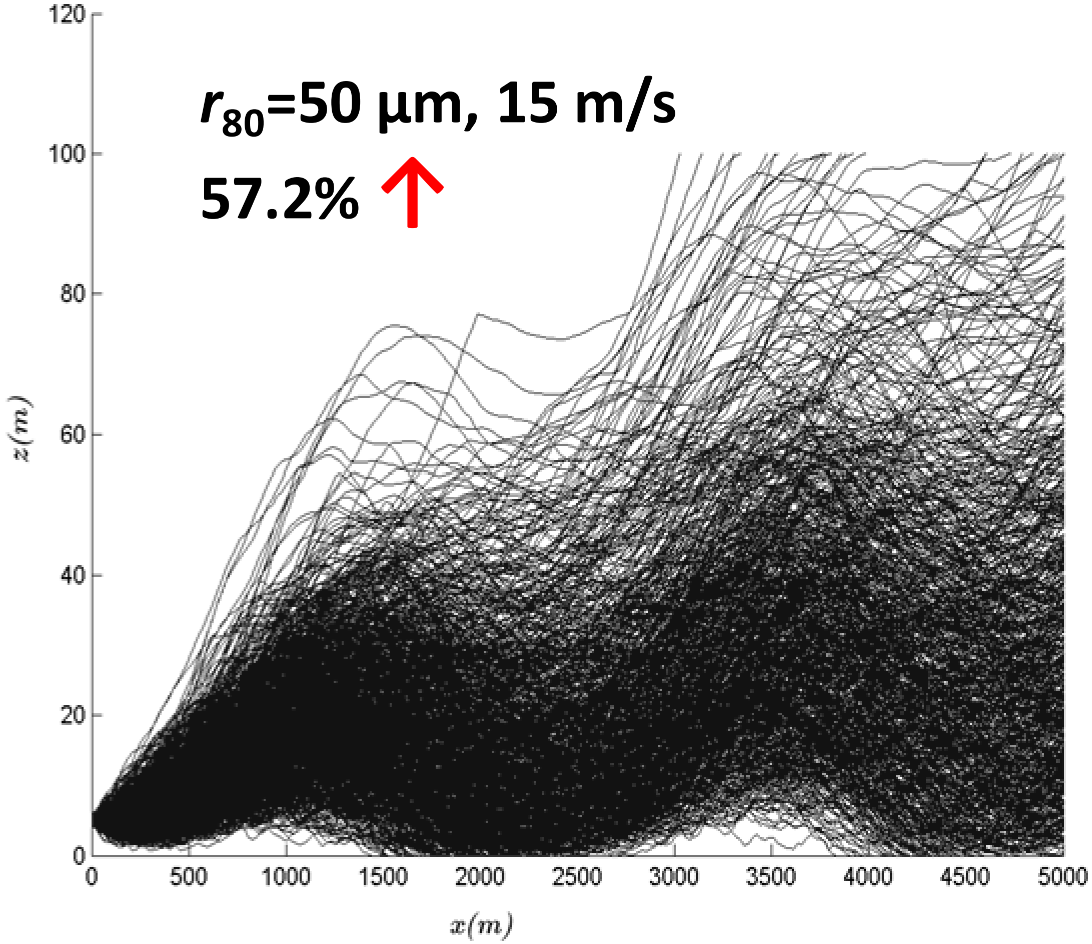
Red： Langevin equation ( *Thomson*, 1987 )

# 3. Resutls

- For $r_{80}$∈[9, 12, 16, 20, 30, 40, 50, 60, 80, 90, 100] μm and $U_{10}$∈[10, 15, 20, 25, 30, 35] m $s^{-1}$, each size-velocity case
- 1,000 particles are calculated and the uplifting ratios are obtained statistically

**Can the large-size spume fly into the 100 m height in ABL?**

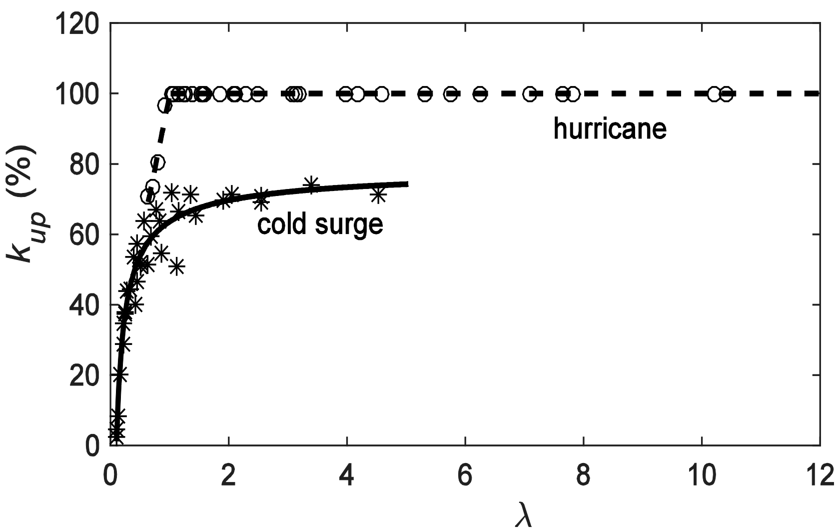
Using the observation data in cold surge,



# The Uplifting Ratio for Spume during Strong Winds (10-35 m s$^{-1}$)

| $U_{10}$ (m/s) \ $r_{80}$(μm), $k_{up}$(%) | 9 | 12 | 16 | 20 | 30 | 40 | 50 | 60 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 50.7 | 54.7 | 51.5 | 51.7 | 44.5 | 37.3 | 28.9 | 20.3 | 8.5 | 4.5 | 2.6 |
| 15 | 69.4 | 69.9 | 65.3 | 66.4 | 66.9 | 63.6 | 57.2 | 53.3 | 44.0 | 37.8 | 34.5 |
| 20 | 71.1 | 73.8 | 71 | 71.4 | 71.3 | 72.1 | 63.8 | 59.3 | 50.9 | 46.6 | 40.2 |
| 25 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 80.3 | 73.2 | 71.0 |
| 30 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99.6 | 96.5 |
| 35 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

**parameterization:** $\lambda = U_{10}^2 / (r_{80} g)$



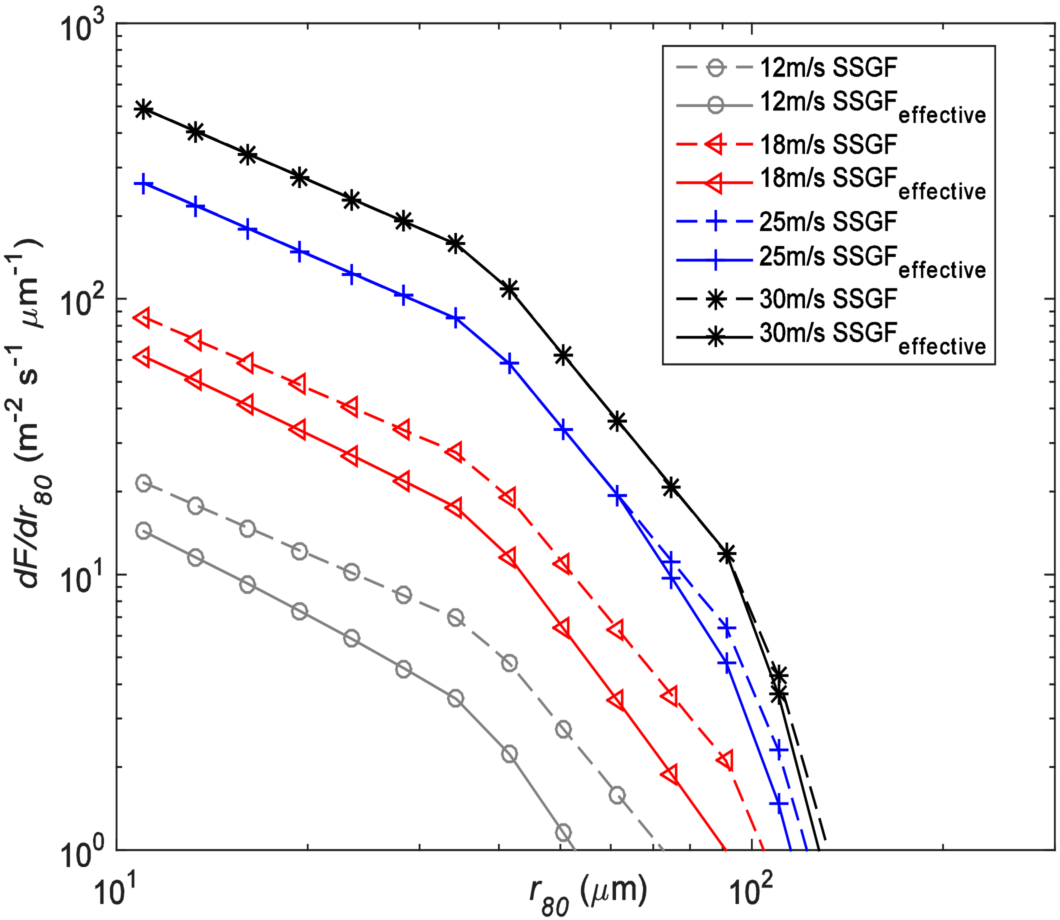

$$k_{up} = \begin{cases} -15.7\lambda^{-0.7} + 79.35, \\ (10 \text{ m s}^{-1} < U_{10} < 20 \text{ m s}^{-1} \text{ and } 0.1 \le \lambda < 4.5) \\ 83.56\lambda + 15.9, \\ (20 \text{ m s}^{-1} \le U_{10} < 35 \text{ m s}^{-1} \text{ and } 0.5 \le \lambda < 1) \\ 100. \\ (20 \text{ m s}^{-1} \le U_{10} < 35 \text{ m s}^{-1} \text{ and } 1 \le \lambda \le 14) \end{cases}$$

# Effective SSGF

The original SSGF for spume (*Andreas*, 1998)

$$\frac{\mathrm{d}F}{\mathrm{d}r_{80}}=\begin{cases} C_1(U_{10})r_{80}^{-1}, & 10\le r_{80}\le 37.5\ \mu\mathrm{m} \\ C_2(U_{10})r_{80}^{-2.8}, & 37.5\le r_{80}\le 100\ \mu\mathrm{m} \\ C_3(U_{10})r_{80}^{-8}, & 100\le r_{80}\le 250\ \mu\mathrm{m} \end{cases}$$

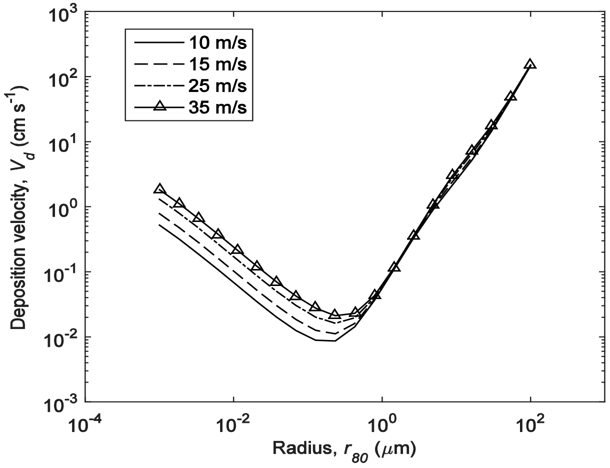
$$\frac{\mathrm{d}F_{\mathrm{up}}}{\mathrm{d}r_{80}}=\frac{\mathrm{d}F}{\mathrm{d}r_{80}}\cdot k_{\mathrm{up}}$$

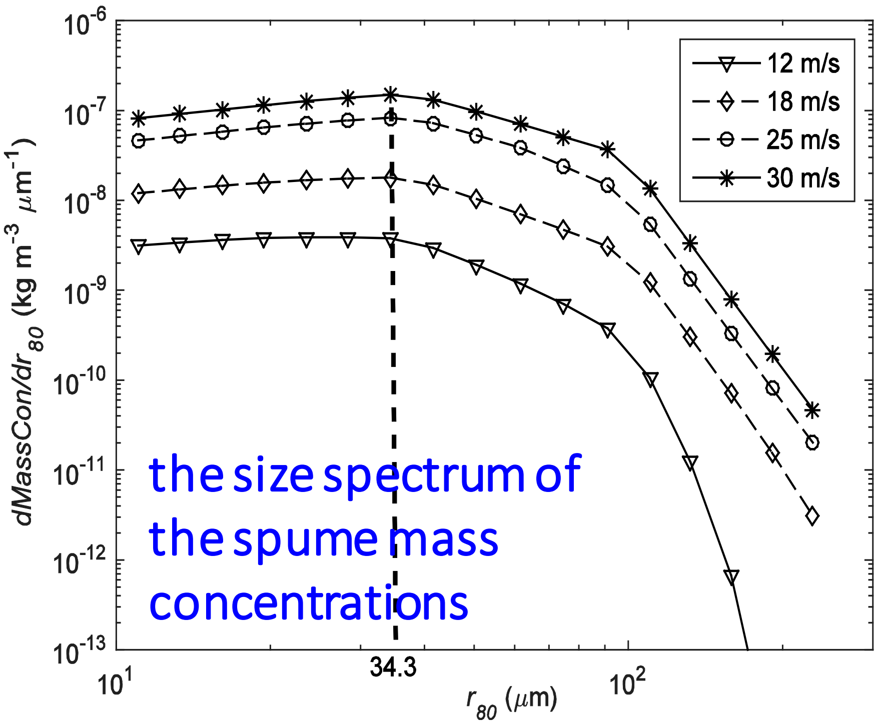



Size spectrum of the uplifted spume droplets at different wind speeds
(dotted line: original; solid: effective)

# Concentration

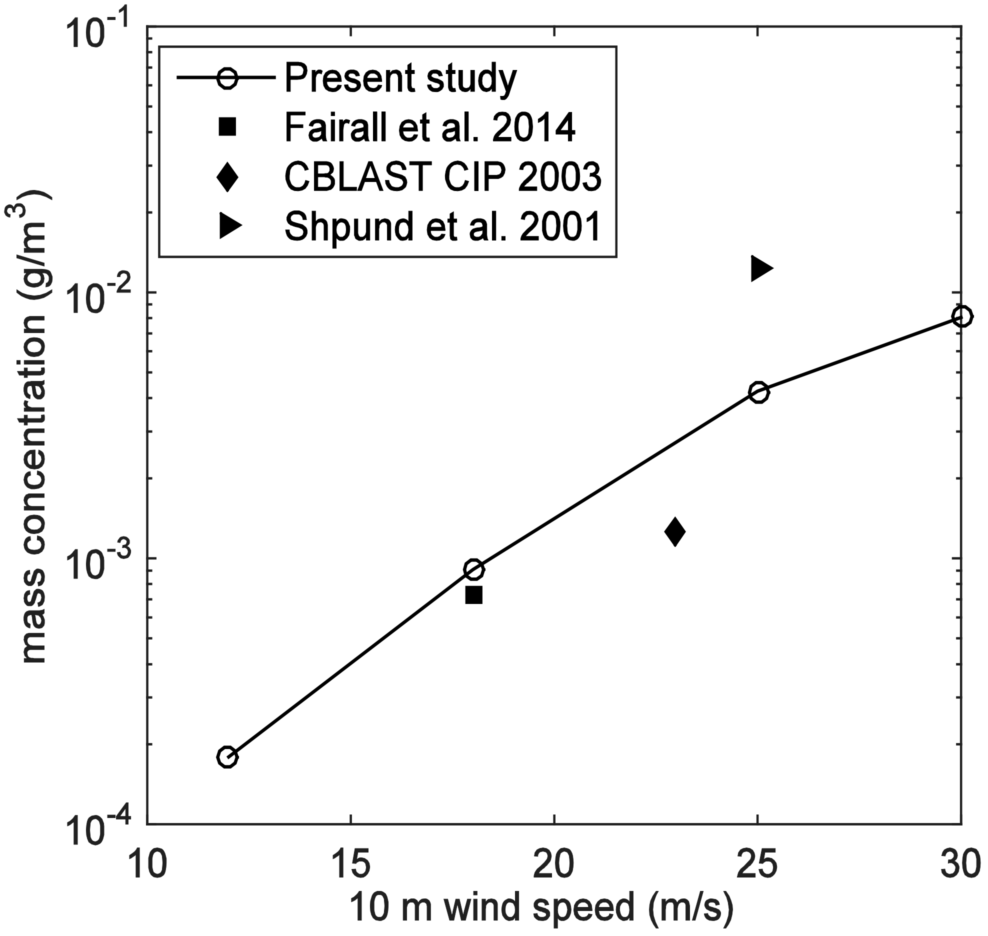
$$\left(\frac{\mathrm{d}N}{\mathrm{d}r_{80}}\right)_i = \left(\frac{1}{V_d}\right)_i \left(\frac{\mathrm{d}F}{\mathrm{d}r_{80}}\right)_i$$




increases slightly with $r_{80}$ until $r_{80}$ reaches 34.3 µm

# Mass concentration & comparisons




spume mass concentration for different wind speeds at 100 m

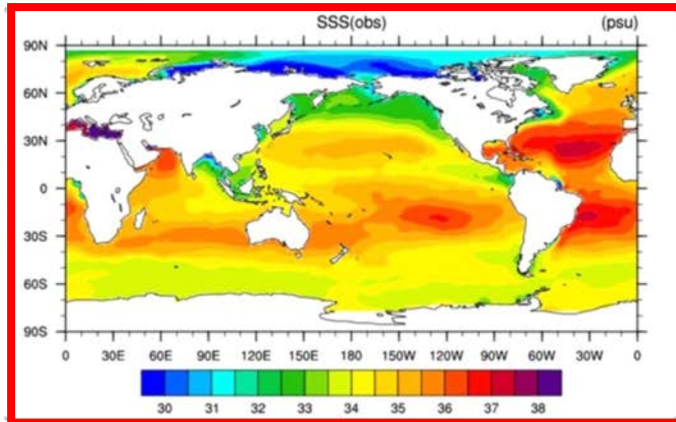
# 4. Conclusions

- Transports of sea-spray spume in high-wind considering the coherent gusts are studied
- Large-size spume can fly into the 100 m height in the atmospheric boundary layer
- The vertical flux and mass concentration of spume are estimated and comparable with the current observations

The ocean generation circulation model

Observations

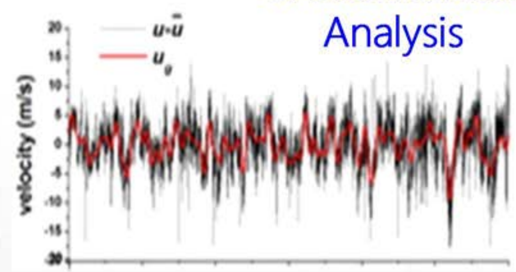
Models

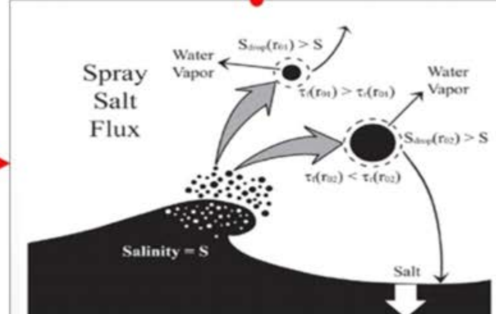



Parameterizations

(SSGF) $\varepsilon$

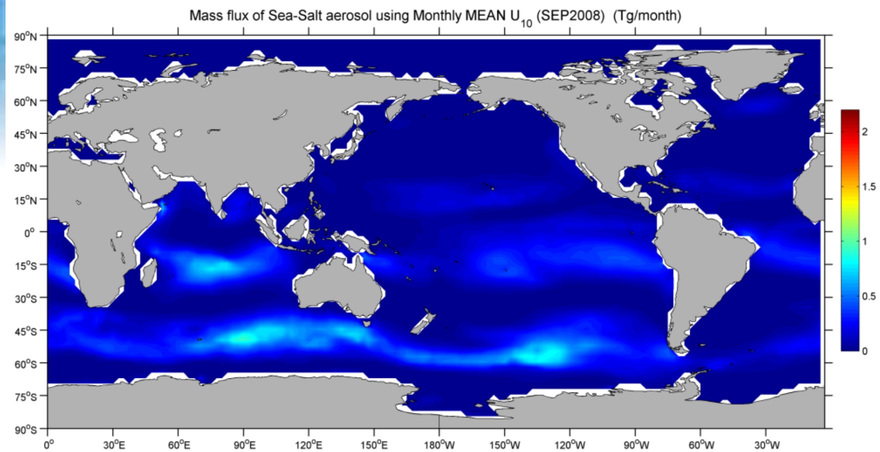
Characteristics Analysis



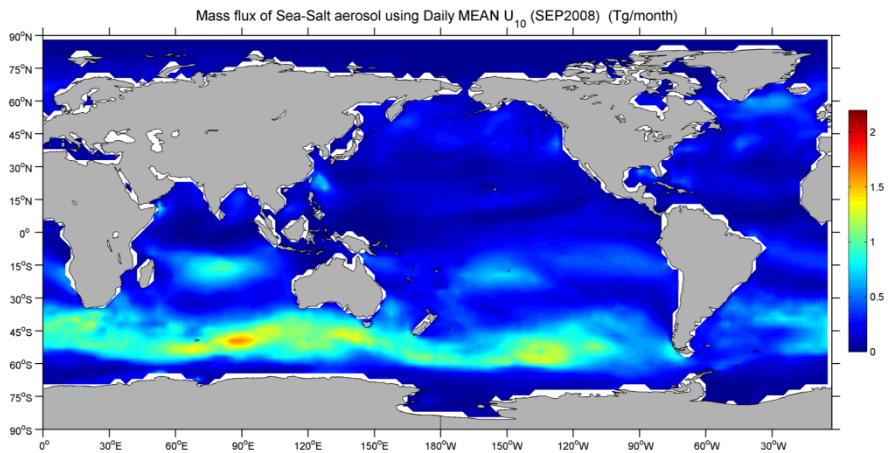




Mechanism & Simulations

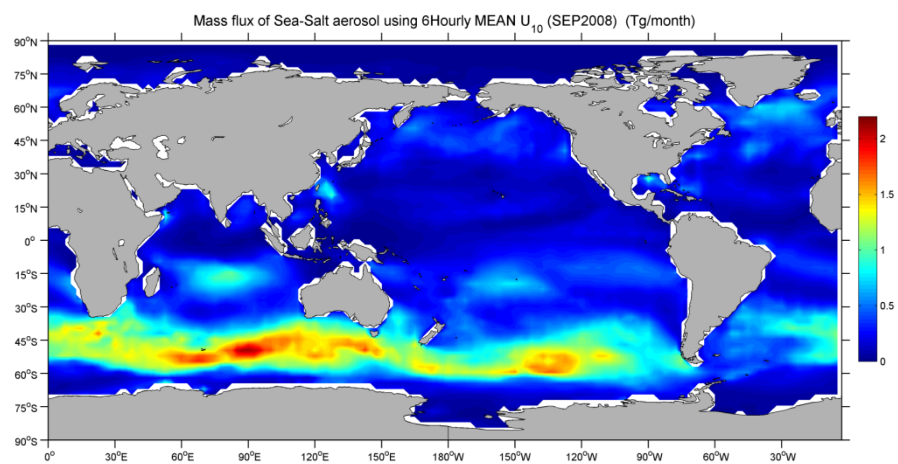
# Thank you for your time and attention




Monthly mean $U_{10}$ : 8.14 Pg/yr




Daily mean $U_{10}$ : 22.71 Pg/yr




6h mean $U_{10}$ : 29 Pg/yr