Sea spray production by bag-breakup mode of fragmentation of the air-water interface at strong and hurricane wind

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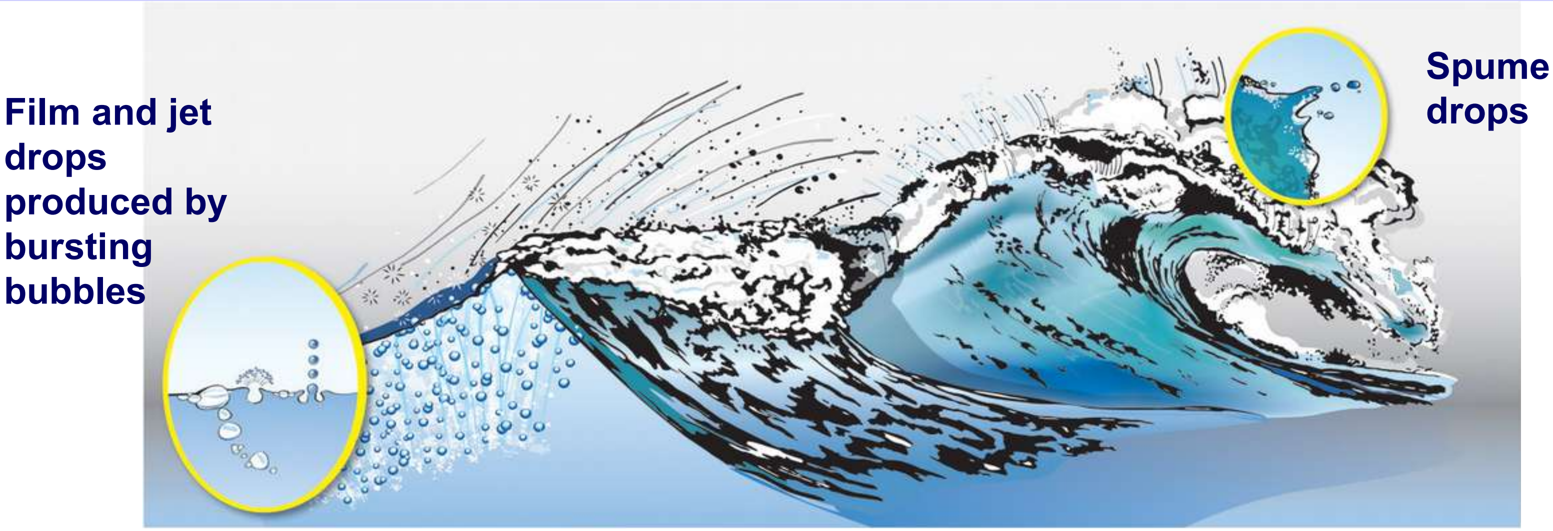
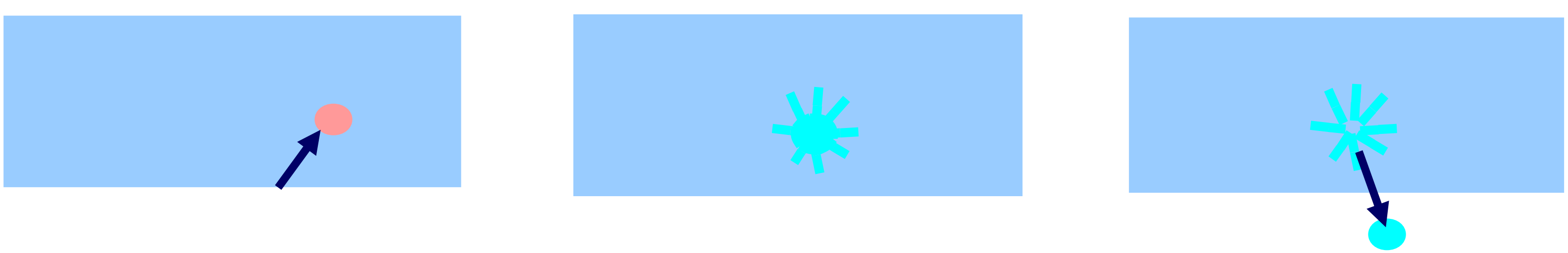


Enhancing the sea-air fluxes at high wind speeds due to sea spray, (Riehl H. 1954. *Tropical Meteorology*)

Only comparatively big droplets contribute to fluxes from the ocean to atmosphere

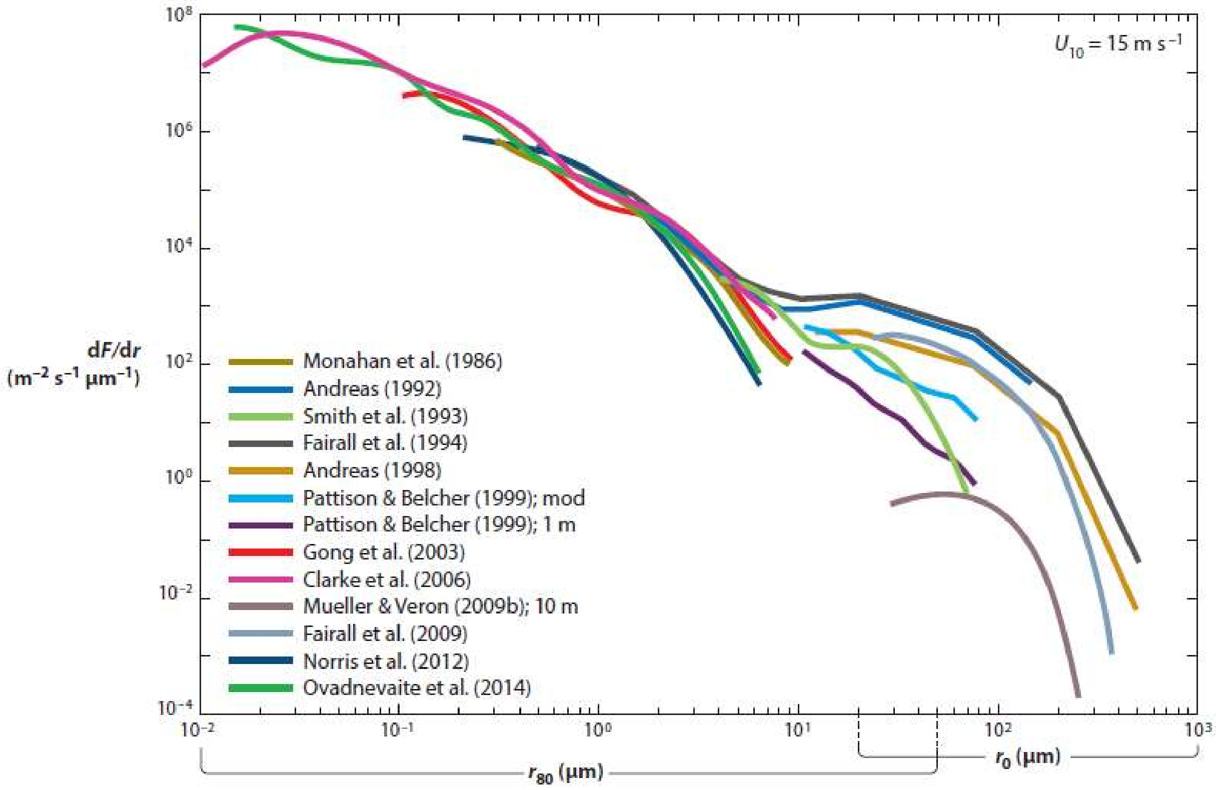
- **momentum flux**
- **moist enthalpy flux according to the concept of re-entrant spray (Andreas, Emanuel, 2001)**



Sea spray that completely evaporate can not affect moist enthalpy transfer, because during the phase transfer they absorb as much sensible heat as they give off in latent heat (Emanuel, 1995)

Sea spray generation function, $U_{10} = 15\ m\ s^{-1}$

Taken from Veron, ARFM, 2015



<u>The reasons of this uncertainty are</u>

1. Difficulties for direct measurements an strong winds
2. Insufficient knowledge of spray generating mechanism.

The purposes of this study are

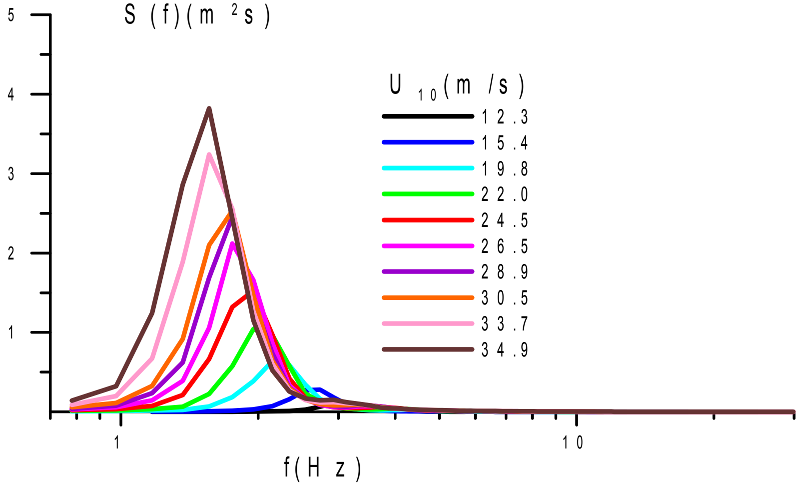
- To investigate of mechanisms responsible for spray generation at strong wind, classify them and quantify the efficiency of the disclosed mechanisms
- To construct the spray generation function at strong winds basing on disclosed mechanisms of their generation
- To estimate momentum and moist enthalpy fluxes at hurricane winds taking into account the effect of spray

The overall view of wind-wave flume

Wind – wave at U_{10}=29 m/s

- Dimensions of the channel
- 10m x 0.4m x 0.4 m
- centerline airflow 3 - 25 m/s
- equivalent 10-m neutral wind speed U_{10} 4 - 40 m/s,

Surface wave frequency spectra



MEMRECAM HX-3

High Speed Camera System

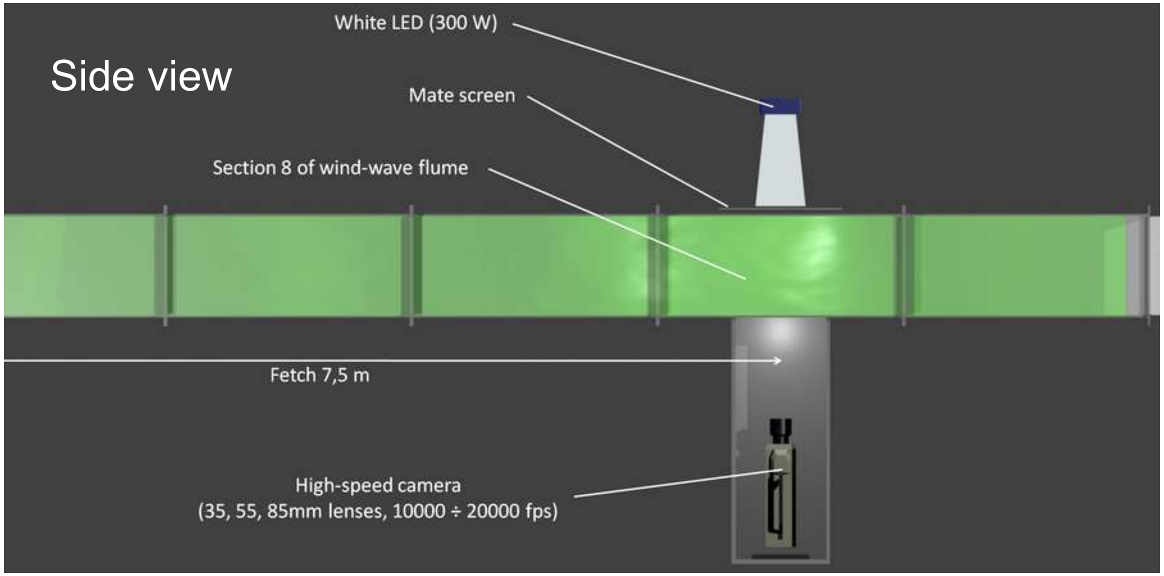
Memrecam HX3 High Resolution Mode		
Max Res (pixels)	2560 X 1920	
Optical Format	35.20 mm	
fps @ Max Res	2,000	
	Mono	Color
ISO Rating	10,000	2,500

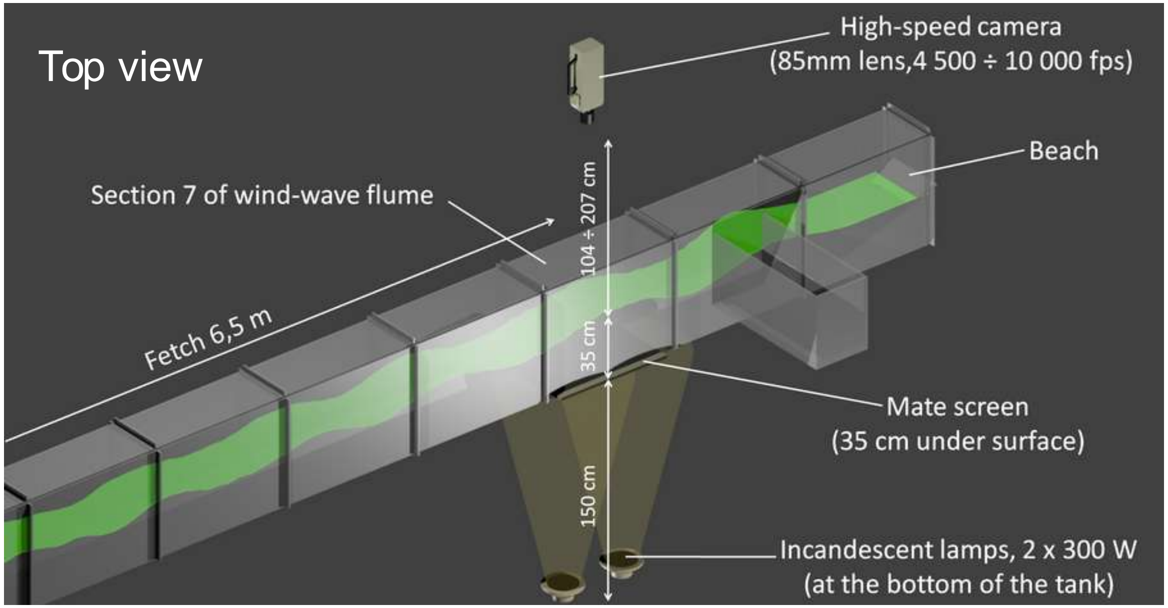
Memrecam HX3 High Speed Mode		
Max Res (pixels)	1280 X 960	
Optical Format	35.20 mm	
fps @ Max Res	7,690	
	Mono	Color
ISO Rating	40,000	10,000

Memory Option	16GB, 32GB, 64GB
Maximum fps	1,300,000

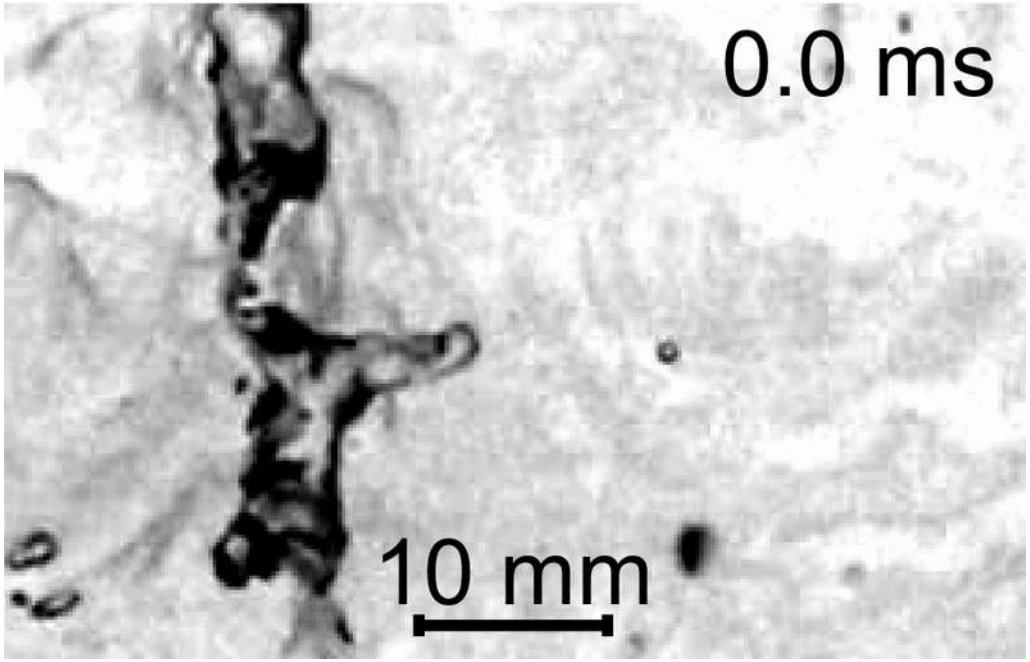
Imaging Formats	Max fps @ Format
High Def: 16 X 9	
1920 X 1080	4,670
1280 X 720	10,230
Other Formats	
4 Mega Pixel	2,400
2 Mega Pixel	4,740
1 Mega Pixel	9,220
XGA (1024 X 768)	11,780
768 X 576	20,230
VGA (640 X 480)	28,310
512 X 512	32,410
512 X 384	43,000
320 X 320	74,340
320 X 240	105,800
320 X 192	130,700
320 X 96	246,880
320 X 48	444,400
320 X 24	740,660

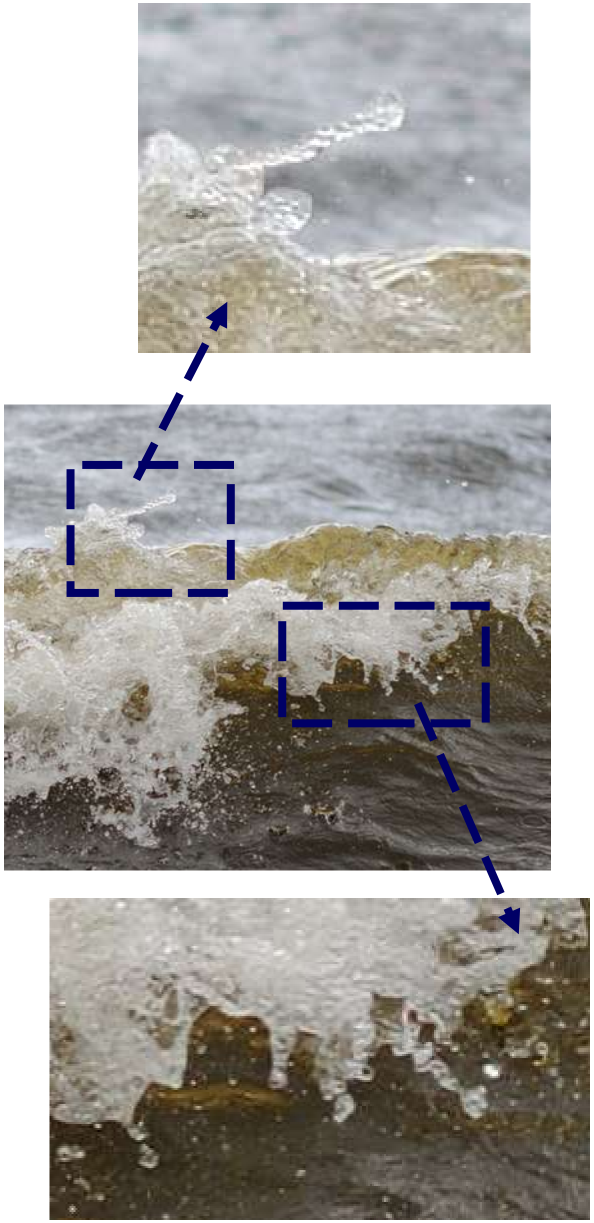
Experimental setup for the shadow method





Spray generation at the wave crests (projections) **Koga, Tellus, 1981**



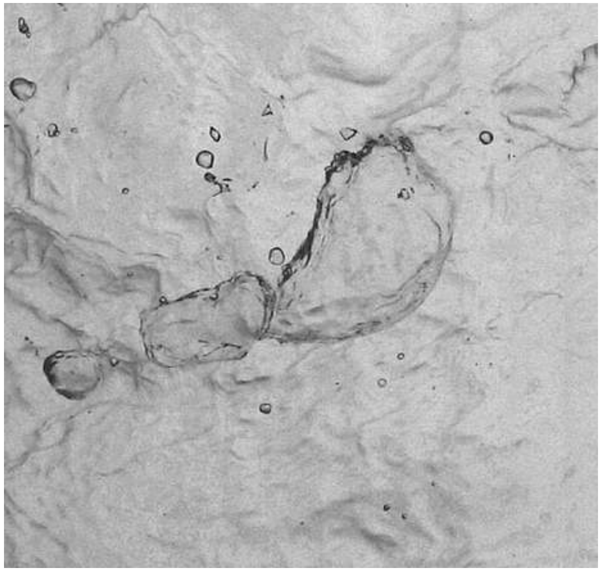


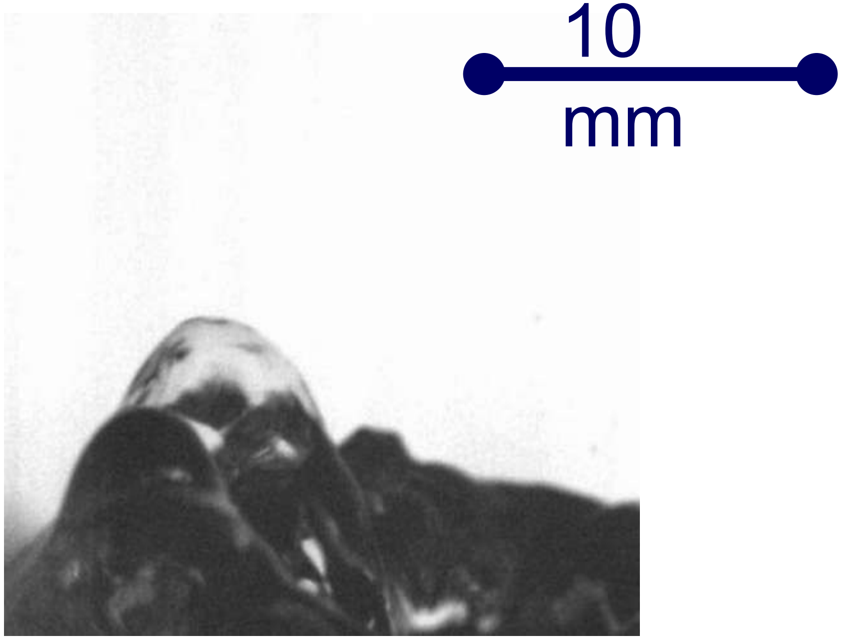
Wind speed
U_{10}=25.9 m/s

f = 85 mm
Samyang 85 mm f/1.4
Distance = 207 cm
Scale = 256 µm/px
4500 fps

Spray generation at the wave crests (underwater bubble)

135 мм





Top view

Wind speed

U_{10}=25.9 m/s

f = 85 mm
Samyang 85 mm f/1.4
Distance = 65 cm
Scale = 73 μm/px
10000 fps

Side view

Wind speed

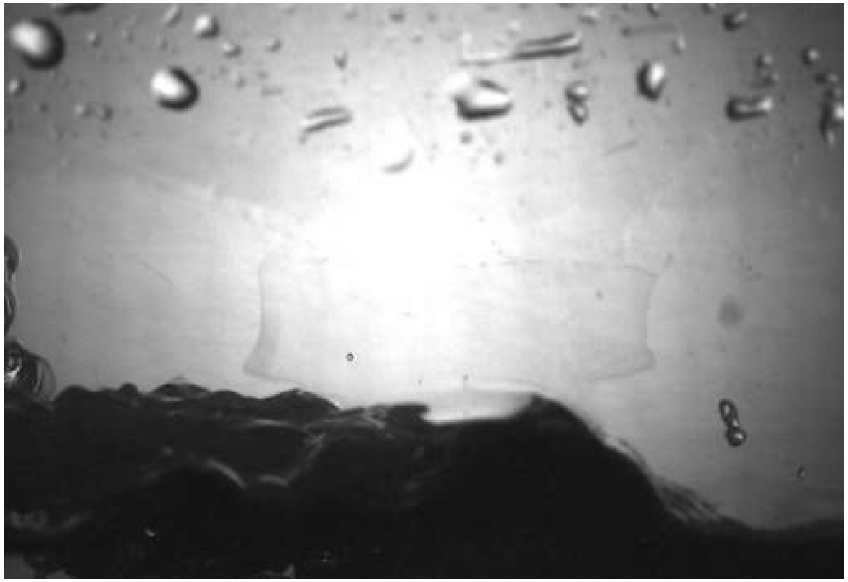
U_{10}=27.8 m/s

- f = 55 mm
- Samyang 85 mm f/1.4
- Distance = 65 cm
- Scale = 73 μm/px
- 2000 fps

H. Lhuissier, E. Villermaux, *J. Fluid Mech.* 696, 5–44 (2012).

Spray generation at the wave crests (“bag breakup”)

(side view)

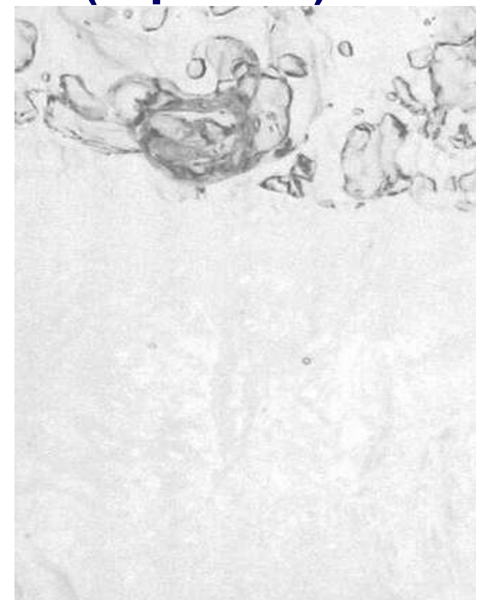


Wind speed
U_{10}=27.7 m/s

Width 74 mm

f = 85 mm (Samyang 85 mm f/1.4)
Distance = 65 cm
Scale = 73 µm/px
10000 fps

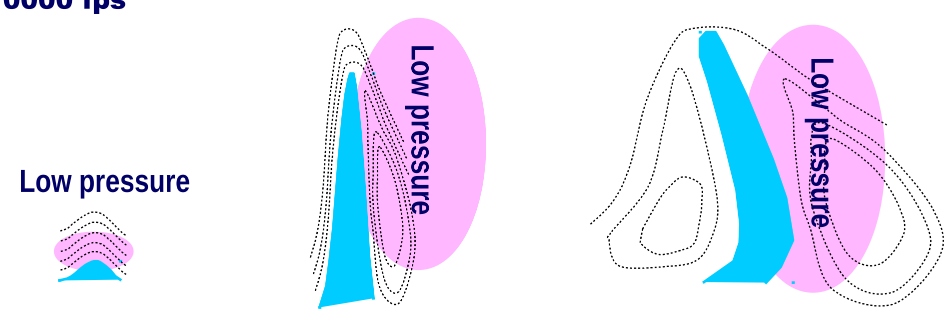
(top view)



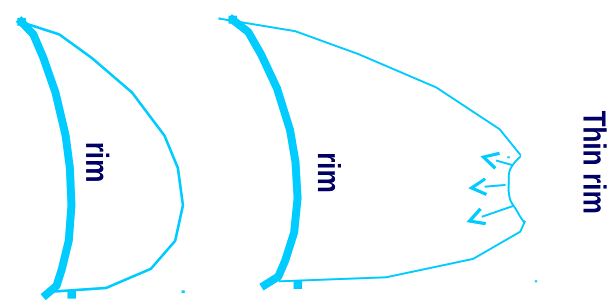
Wind speed
U_{10}=26.7 m/s

Width 70 mm

f = 85 mm (Samyang 85 mm f/1.4)
Distance = 207 cm
Scale = 256 µm/px
4500 fps



H. Branger, private communication

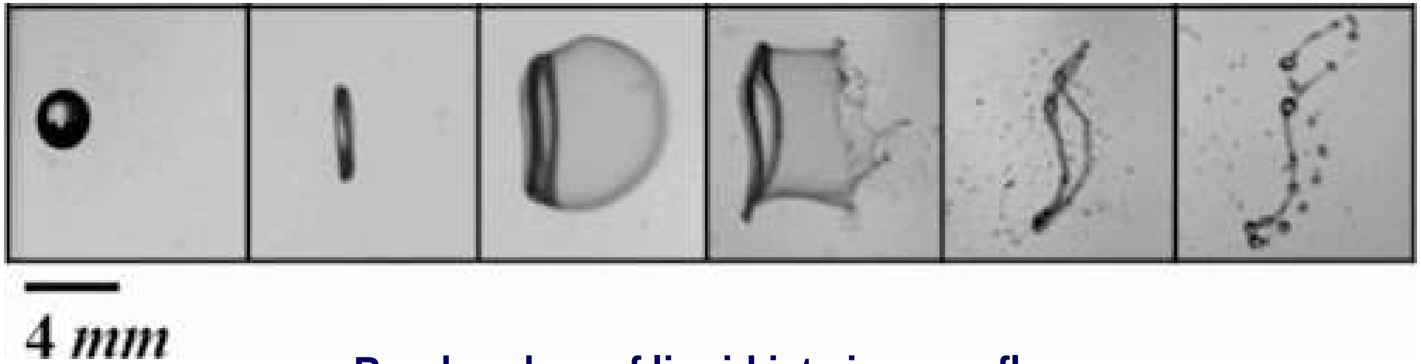


F. Veron, etal, 2012

“Bag breakup” (moderate $We = \dfrac{\rho_a U^2 R}{\sigma}$)

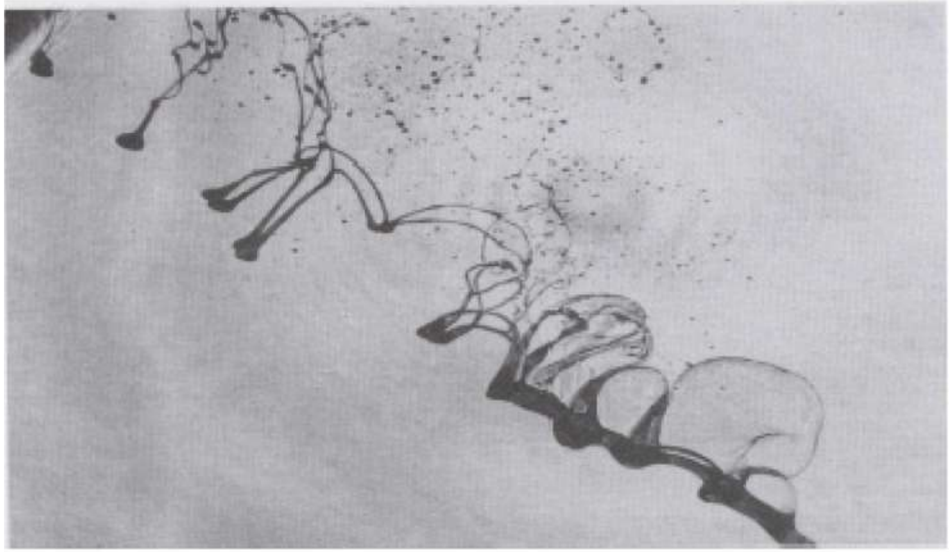
Bag-breakup mode of fragmentation of a droplet

V. Kulkarni and P. Sojka Phys. Fluids 26, 072103 (2014)



Bag-breakup of liquid jets in crossflow

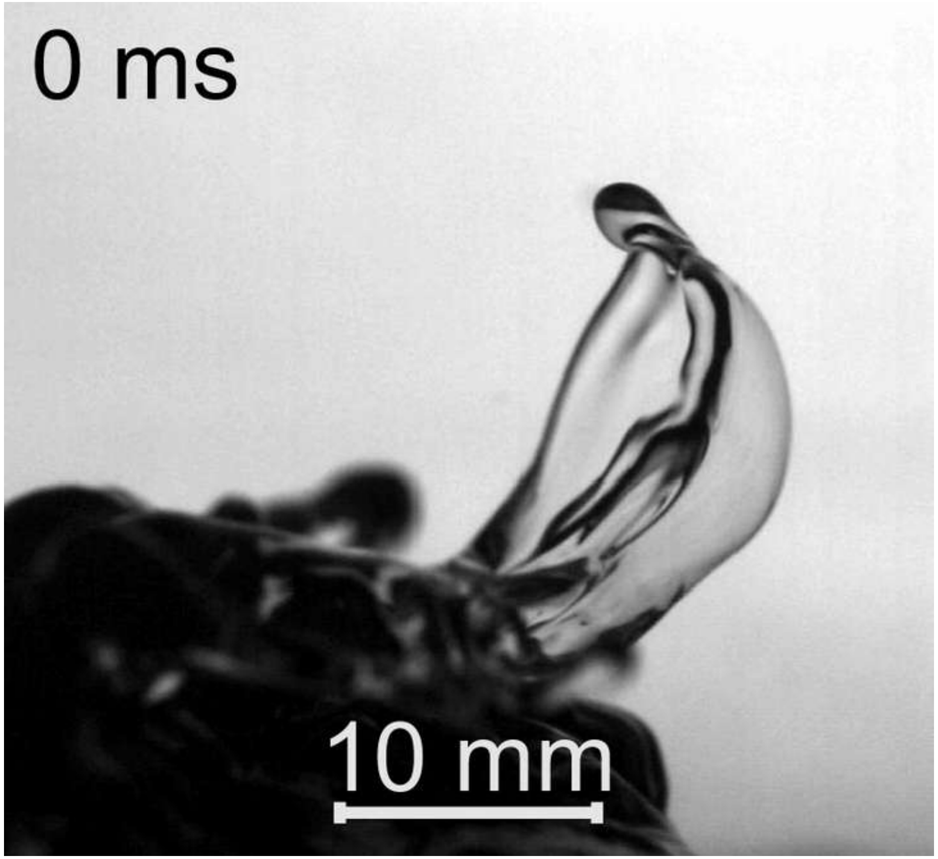
Ashgriz, N. Atomization of a liquid jet in a crossflow. In Proceedings of the 4th International Meeting of Advances in Thermofluids, Melaka, Malaysia, 3–4 October 2011.



Bag breakup
(side view)

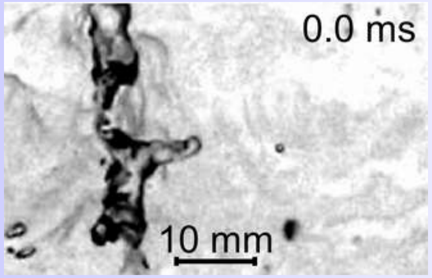
Wind speed
U_{10}=27.8 m/s

- **f = 55 mm**
Samyang 85 mm f/1.4
- **Distance = 65 cm**
- **Scale = 73 μm/px**
- **2000 fps**



10 mm

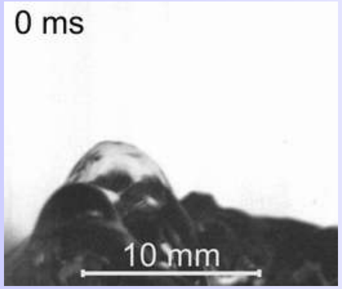
Spray generation mechanisms



Projections (top view)

Wind speed
U_{10}=25.9 m/s

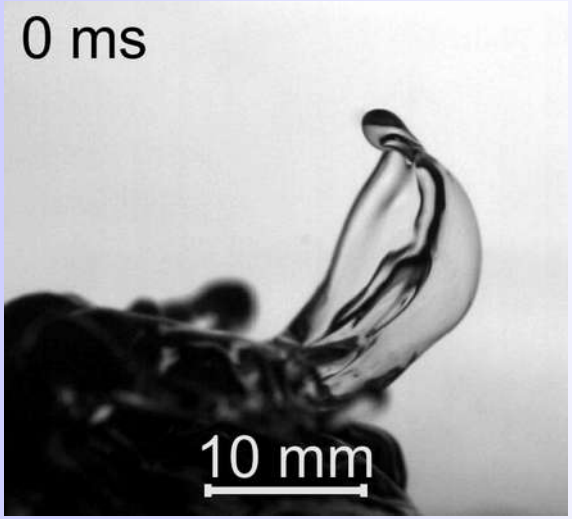
f = 85 mm
Samyang 85 mm f/1.4
Distance = 65 cm
Scale = 73 µm/px
10000 fps



Underwater bubble (side view)

Wind speed
U_{10}=27.8 m/s

- f = 55 mm
Samyang 85 mm f/1.4
- Distance = 65 cm
- Scale = 73 µm/px
- 2000 fps

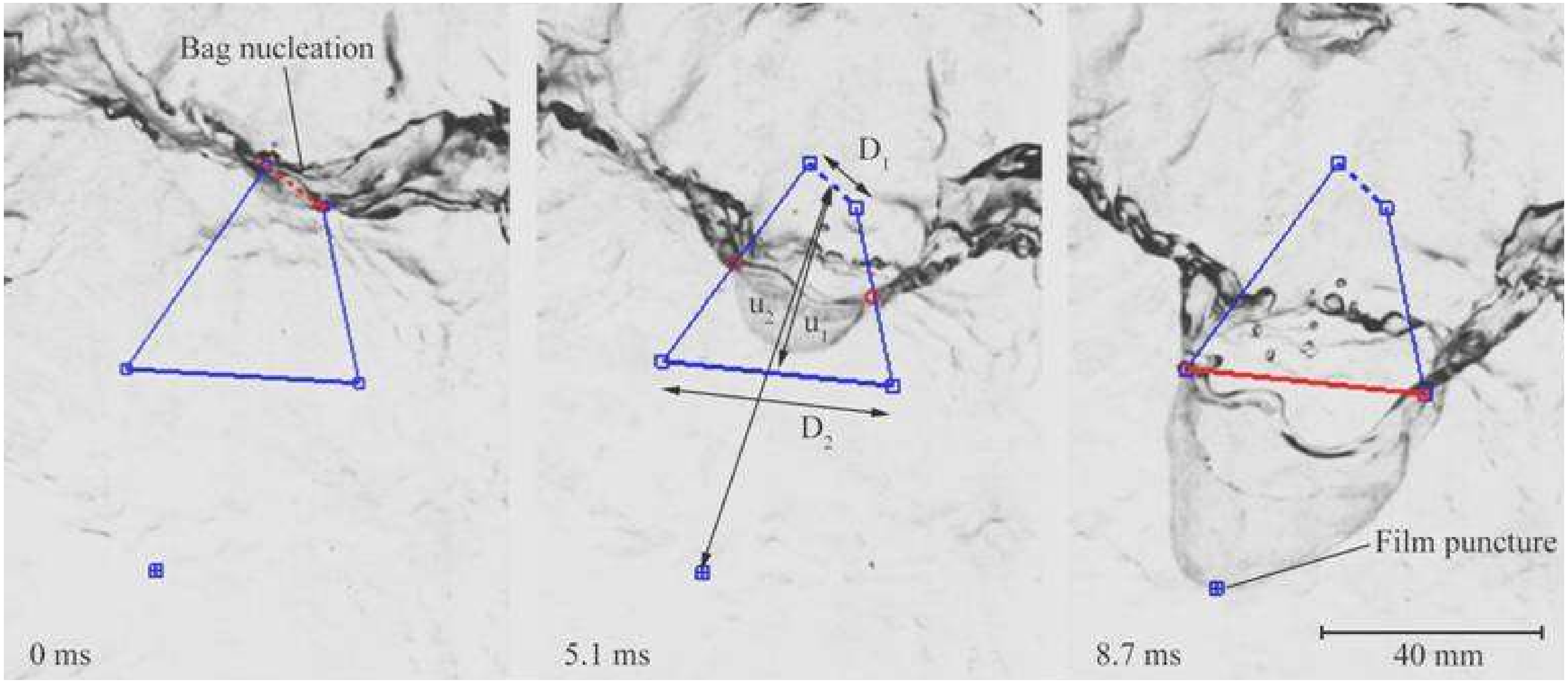


Bag breakup (side view)

Wind speed
U_{10}=27.8 m/s

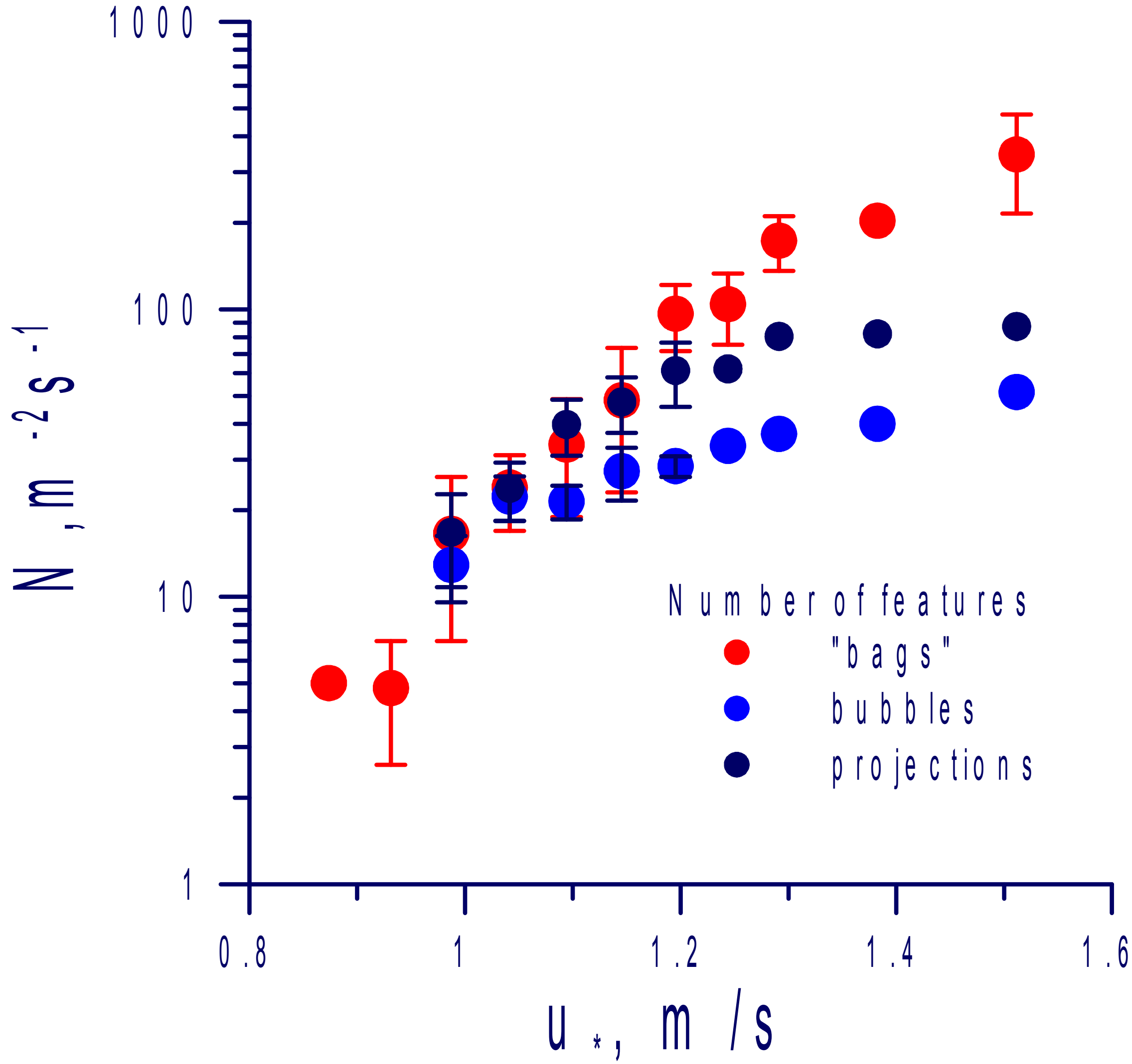
- f = 55 mm
Samyang 85 mm f/1.4
- Distance = 65 cm
- Scale = 73 µm/px
- 2000 fps

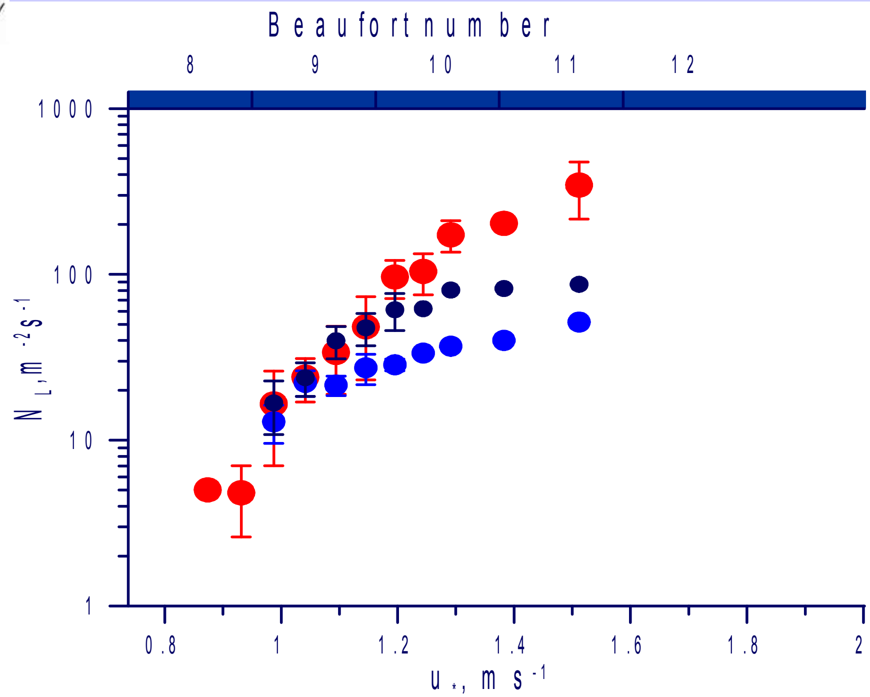
Semi-automatic processing of images



Statistics: about 70 video containing about 33000 frames each

Specific number of local spray generating phenomena (per unit time per unit area) versus friction velocity





The bag-breakup activation threshold u_* approximately corresponds to gale force wind, or Force 8 wind in Beaufort scale.

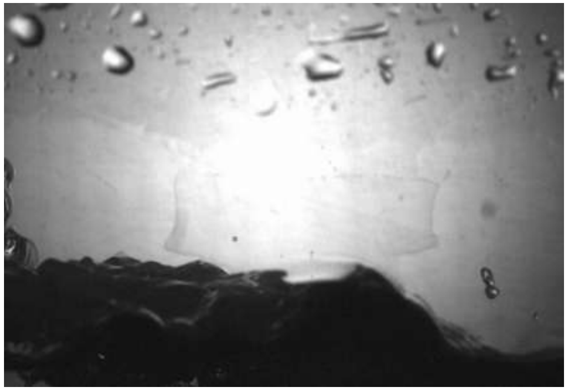
The Beaufort scale based on the sea's appearance. Wind force 8: "*Moderately high waves with breaking crests forming* ***spindrift.***

spindrift — ► spray blown from the crests of waves by the wind

"Spindrift", 25 fps

Wave crest, 2000 fps

Bag-breakup, 10000 fps



Phenomenological “statistical-physics" approach to describe the statistics of "bags”

Consider the wave crests that can be potentially transformed to bags (or broken to “spindrift”) as a “subsystem” in equilibrium with the “thermostat” – air-sea boundary layer.
The statistical distribution of energy states of this subsystem is determined by the Gibbs or canonical distribution

$$dW = \alpha \, e^{-\frac{E}{\beta}} dE$$

α и β - functions of wave fetch and wind speed

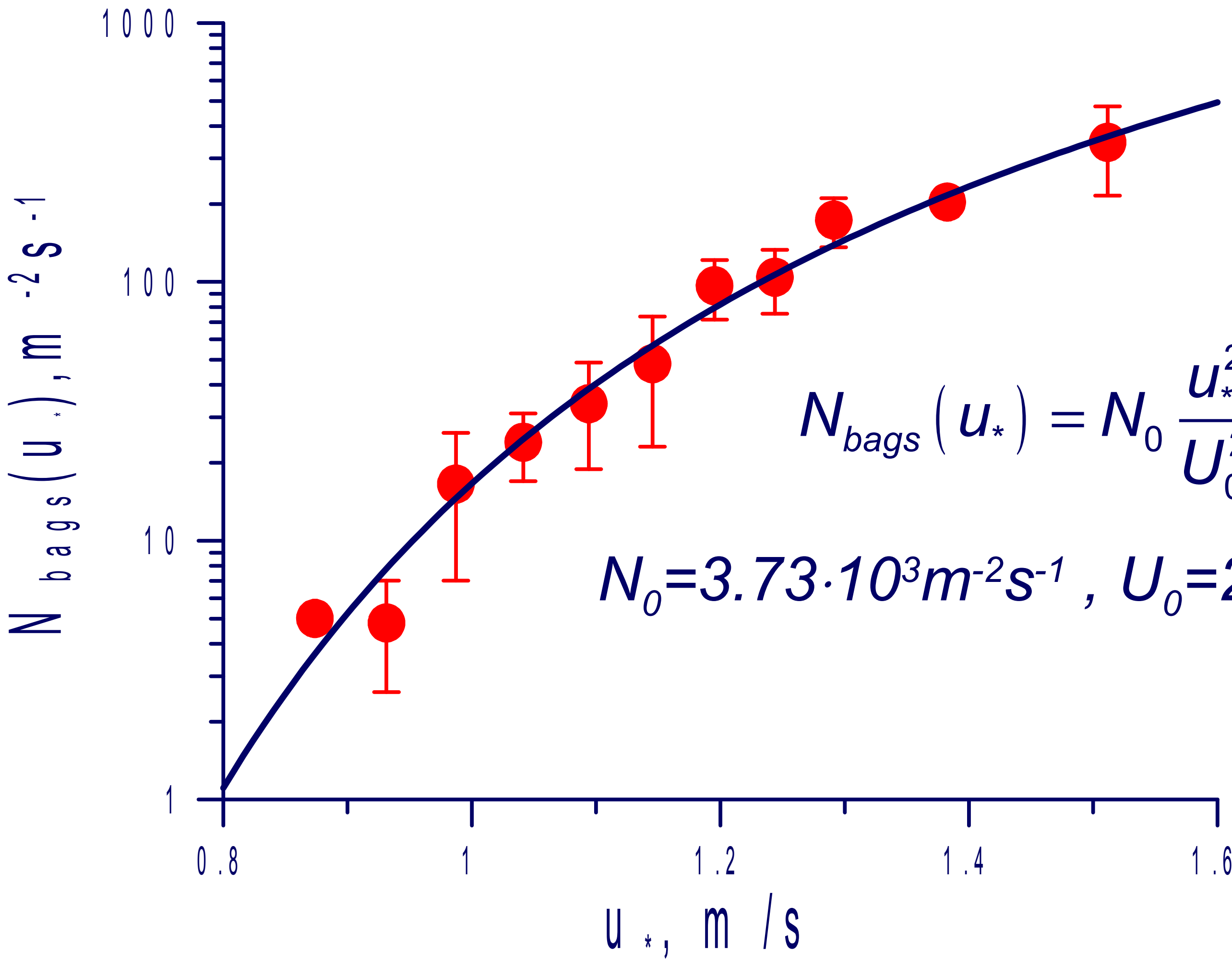
Similarly to thermodynamics $\beta \sim u_*^2$

(The Boussinesq analogy between the turbulent velocity fluctuations and the thermal motions of molecules in gas.)

The bags’ regime requires the finite minimum energy of the subsystem for activation. Then, their total number of “bags” is proportional to the probability that the subsystem energy exceeds this minimum value, denoted U_0^2

$$N_{bags}\left(u_*\right) = \int_{U_0^2}^{\infty} A e^{-\frac{E}{u_*^2}} dE = A u_*^2 \exp\left(-\frac{U_0^2}{u_*^2}\right)$$

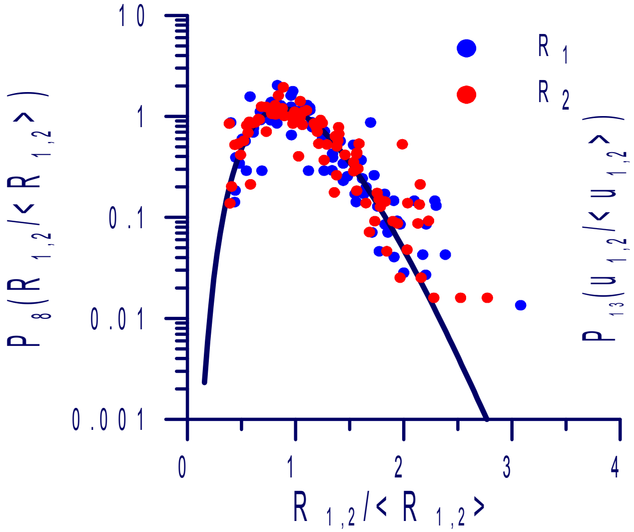
Number of “bags” unit time per unit area versus friction velocity

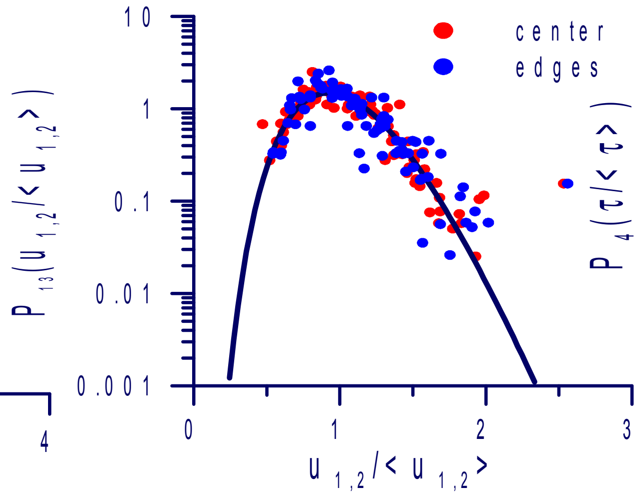


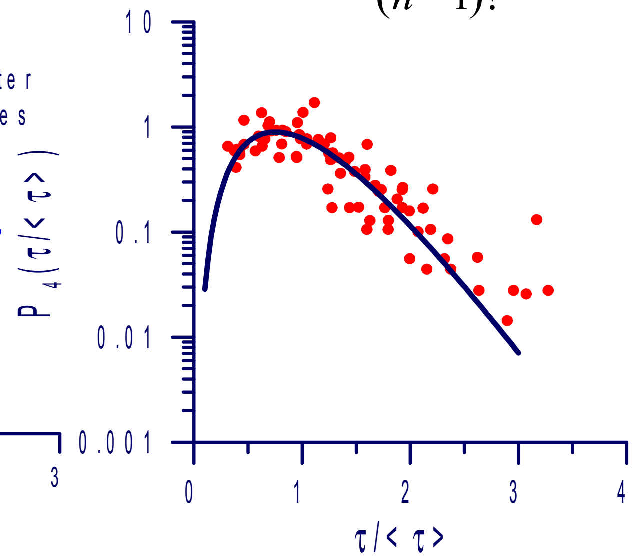
$$N_{bags}\left(u_*\right)=N_0\frac{u_*^2}{U_0^2}e^{-\frac{U_0^2}{u_*^2}}$$

$N_0=3.73\cdot10^3 m^{-2}s^{-1}$, $U_0=2.0$ m/s

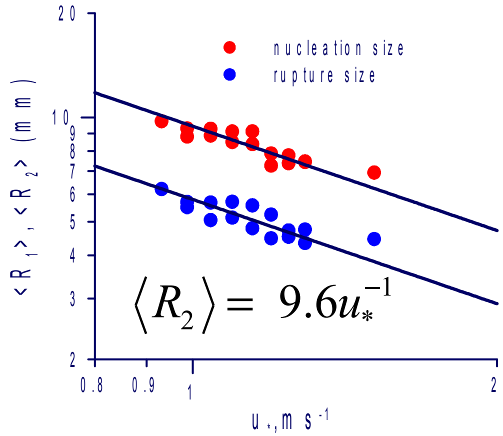
Distribution of "bags" over sizes, velocities and lifetimes $P_n(x) = \frac{n^n}{(n-1)!} x^{n-1} e^{-nx}$

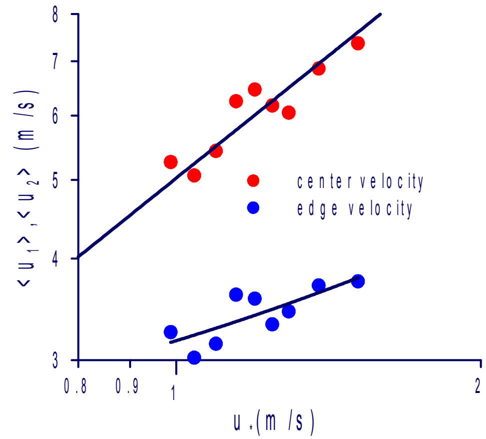


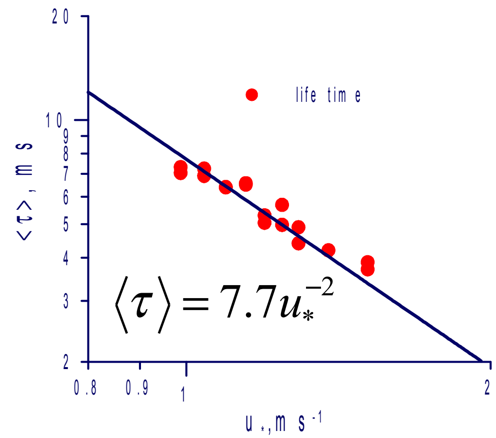




Average sizes, velocities and lifetimes of "bags" via wind friction velocity







Scales of "bags" $\delta_{vis} \sim \nu/u_*; \tau_{vis} \sim \nu/u_*^2$ are controlled by viscosity

SSGF is a convolution of the size spectra of bags with the size spectra of droplets produced by a sole bag

$$\frac{dF(r)}{dr} = \frac{N_{bags}(u_*)}{\langle R\rangle(u_*)} \int P_8\left(\frac{R}{\langle R\rangle(u_*)}\right) F_{drops}(r,R)\,dR$$

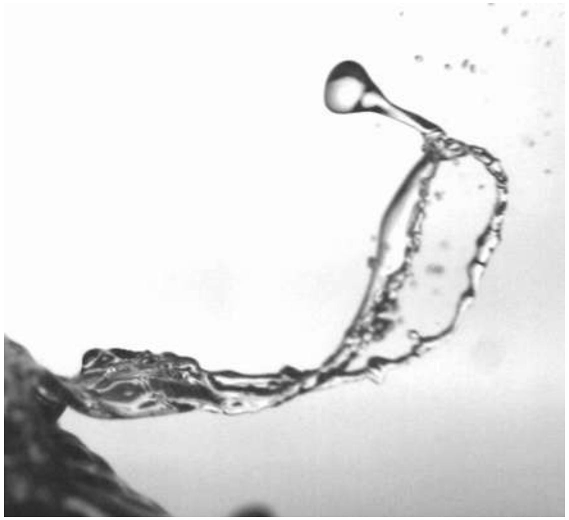
“Bags” generate spray in two ways

1. Rupturing the film of inflated bag

“Film droplets”

r~100 μm

2. Fragmentation of the rim



“Rim droplets”

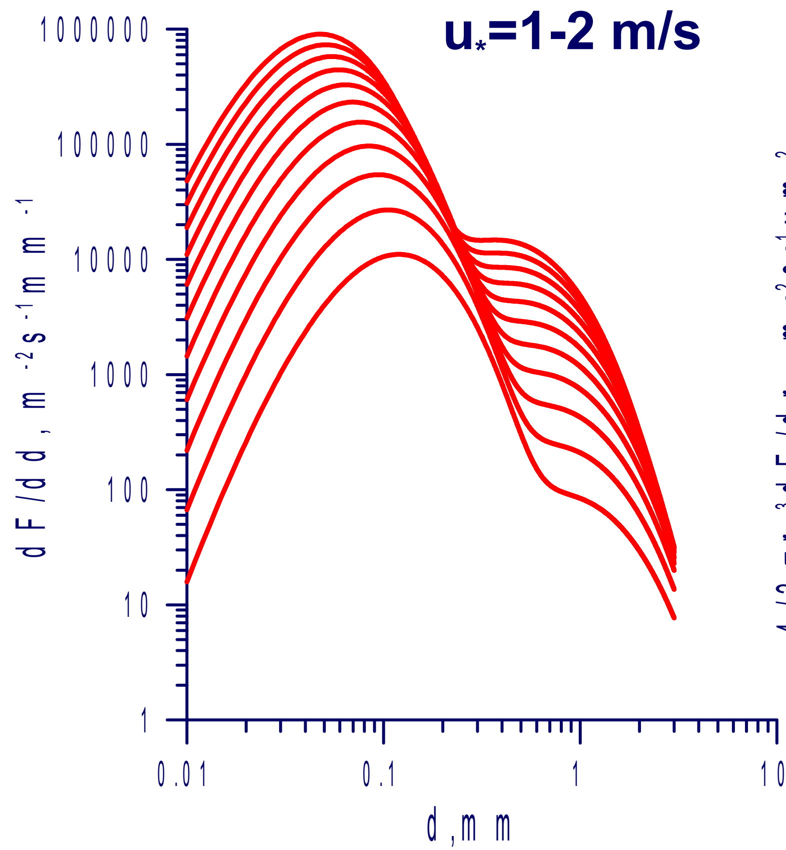
A “hallmark” of bag-breakup

r~1000 μm

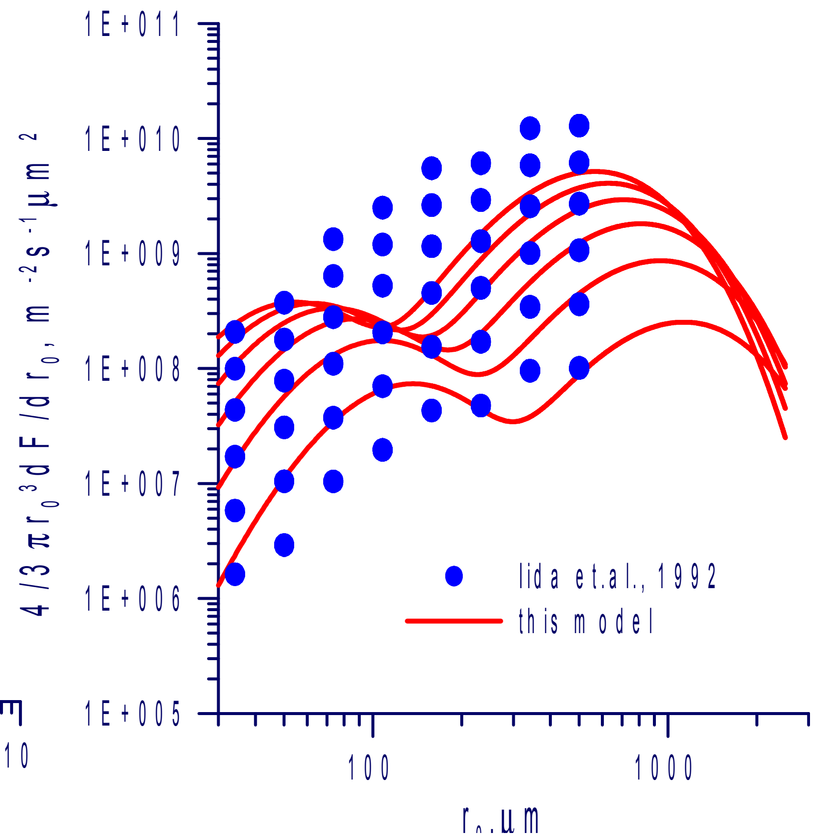
$$F_{drops}(r,R) = F_{film}(r,R) + F_{rim}(r,R)$$

“Bag breakup” SSGF at wind friction velocities *u** from 1 m/s to 2 m/s with increment 0.1 m/s

$$\frac{dF(r,u_*)}{dr} = N_{bags}(u_*)\left(A_1 r^{\frac{15}{2}} e^{-\alpha_1 \sinh\left(\frac{3}{7}\ln\frac{r}{\delta}\right)} + A_2 r^{\frac{19}{4}} e^{-\alpha_2 \sinh\left(\frac{1}{2}\ln\frac{r}{\Delta}\right)} \right)$$



SSGF as a volume flux



Comparing of the model with available field experiments

Zhao et.al. (2006): $R_{WS} = \dfrac{u_*^2}{\nu \omega_p}$ $\dfrac{dF(r,u_*)}{dr} \sim Re_{WS}^{1.5}$

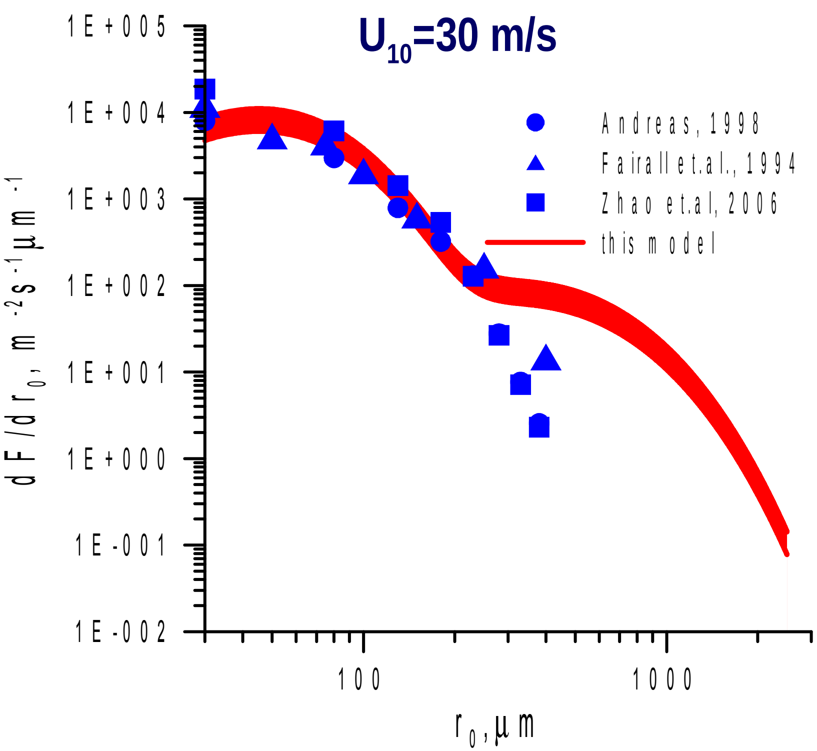
$$\omega_{p-lab} = 12.4 u_*^{-0.5}$$

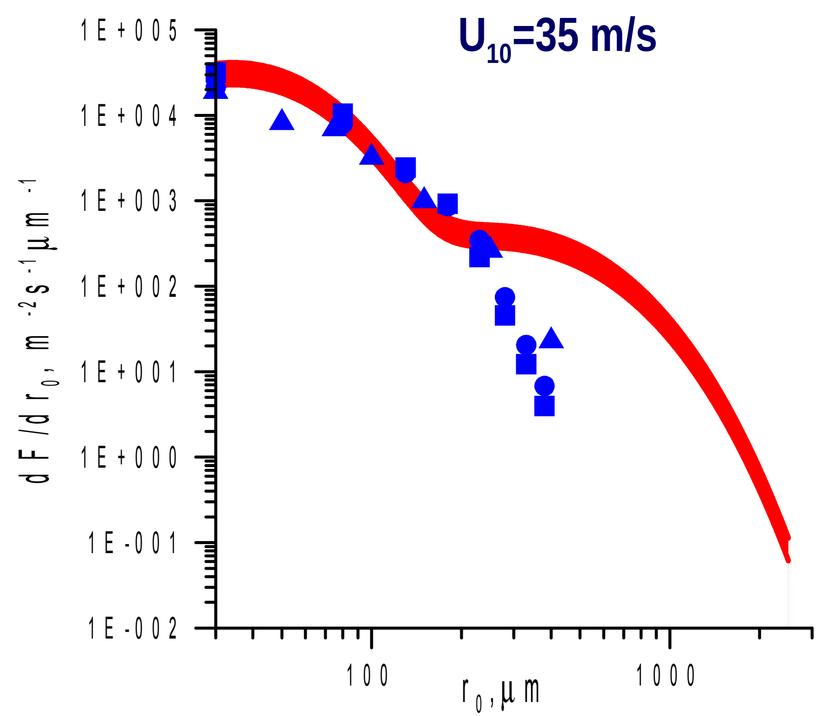
$$\omega_{p-field} = g\Omega / U_{10} = g\Omega\sqrt{C_D}/u_*$$

$$\Omega = U_{10}/c_p$$

$$\frac{dF_{Field}(r,u_*)}{dr} = \frac{dF_{Lab}(r,u_*)}{dr}\left(\frac{12.4u_*^{0.5}}{g\Omega\sqrt{C_D}}\right)^{1.5}$$

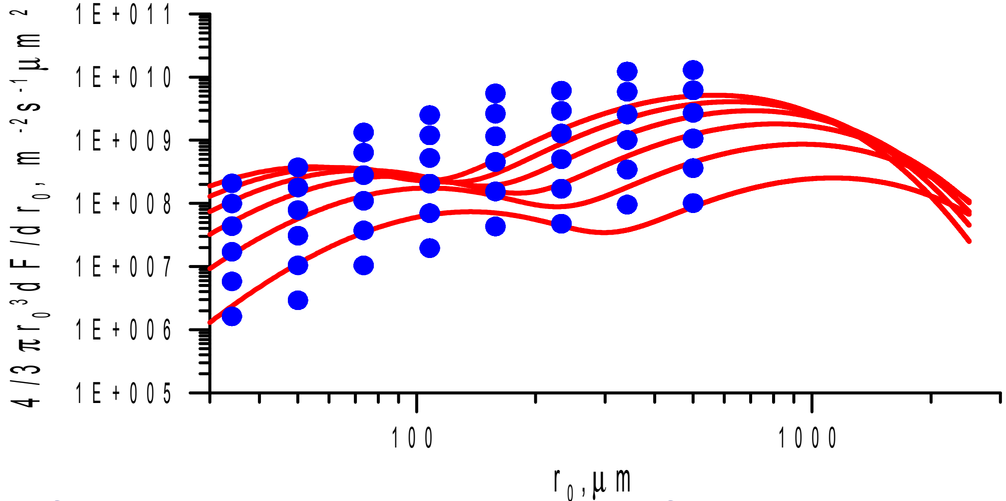
Ω=2.5-3.5 (data by Wright, etal., 2001)





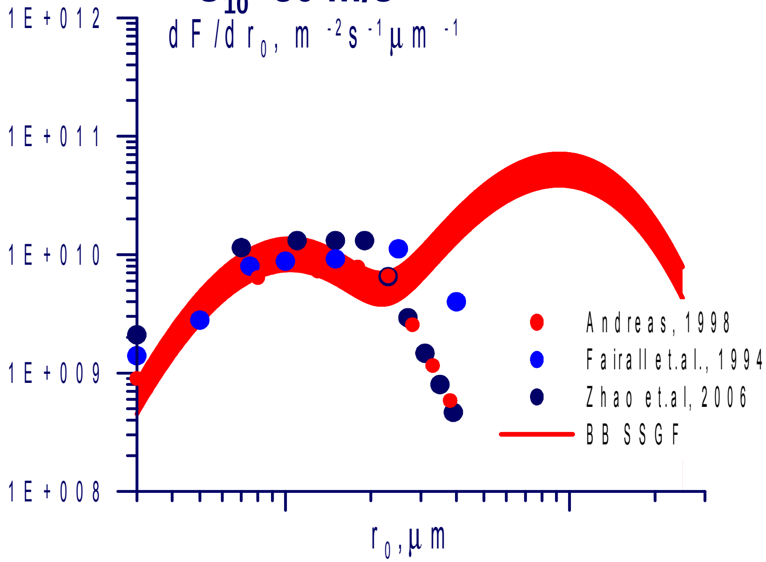
SSGF as a volume flux

Comparing of the model with available lab experiments

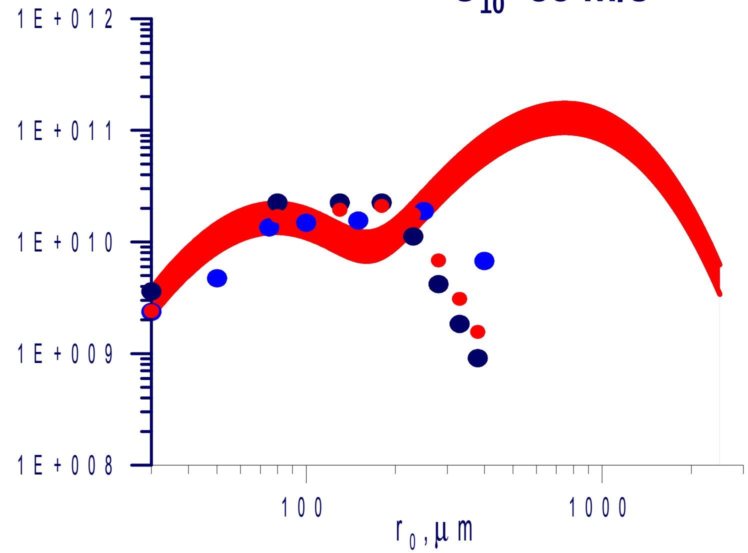


Comparing of the model with available field experiments Ω=2.5-3.5

U_{10}=30 m/s



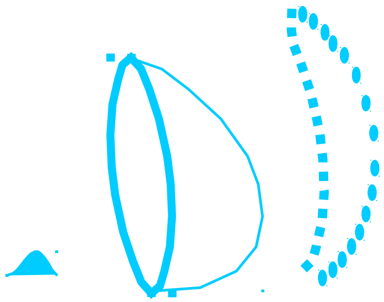
U_{10}=35 m/s



Effect of the “bag-breakup” on air-sea fluxes.

Effect on air-sea momentum flux (tangential stress).

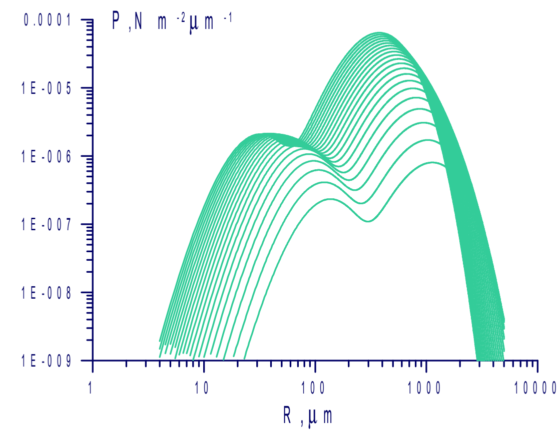
1. The “droplet” stress determined by the momentum acquired by droplets in the process of their production



$$F_{MSpray} = \rho_w \int_0^{\infty} \frac{dF(r, u_*)}{dr} \frac{4\pi r^3}{3} u_{Spray}\, dr$$

$$u_{Spray} = \langle u_1 \rangle = 1.21 u_* + 1.96$$

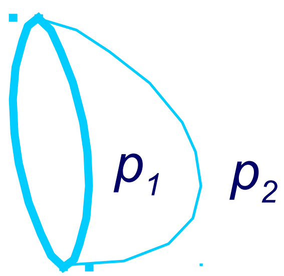
Contribution of droplets to enthalpy flux, U_{10}=20-60 m/s



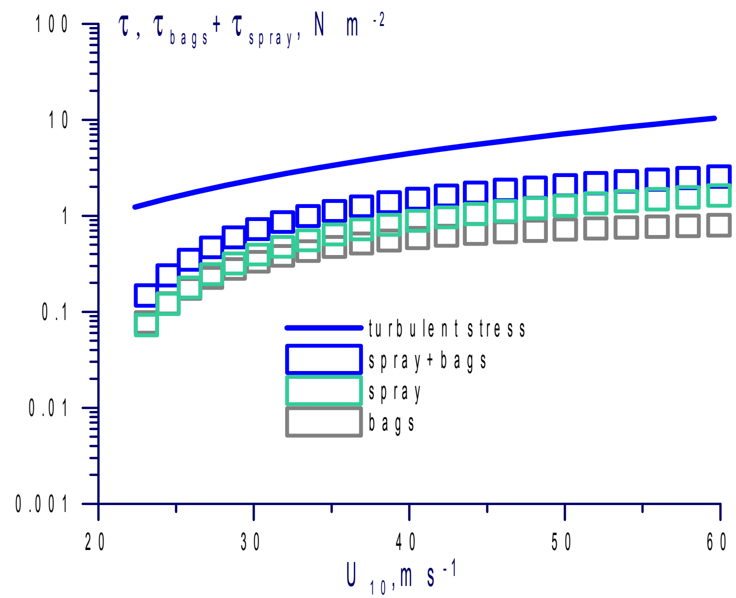
2. The “bag” stress provided by bags, “micro sails” with typical sizes about 1 cm, making obstacles to the near-water airflow

The force on a "bag" as an obstacle to wind

$$\vec{f}(t) = \iint_S (p_1 - p_2)\vec{n}\, ds$$



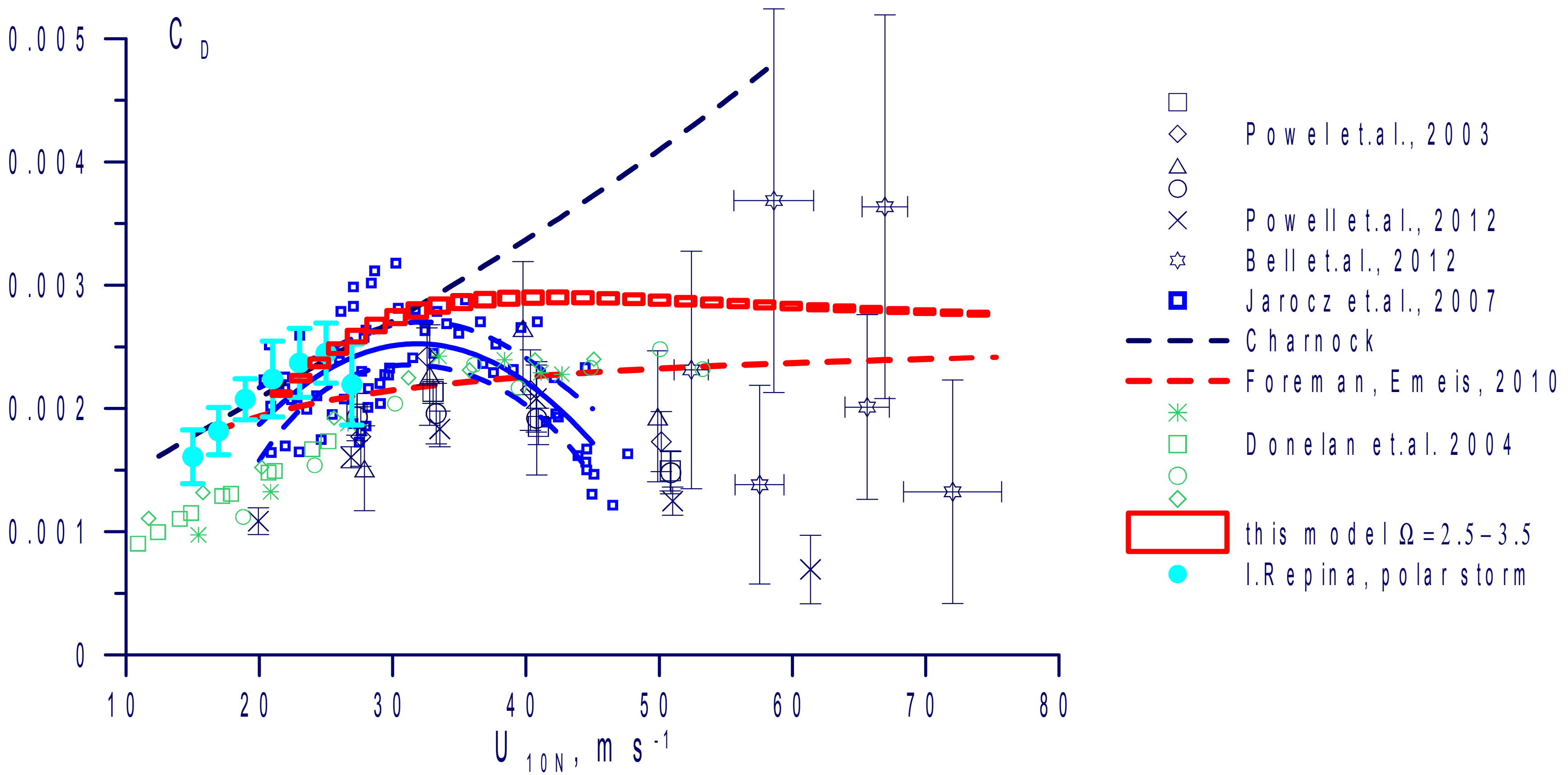
$$(p_1 - p_2)\big|_S = \frac{4\sigma}{R(t)}$$



Effect of spray on transfer coefficients

Sea surface drag via wind speed (hurricane)

$$F_M = F_{Mwaves} + F_{Mbags} + F_{Mspray};\ C_{D10} = F_M / \rho_a U_{10}^2$$

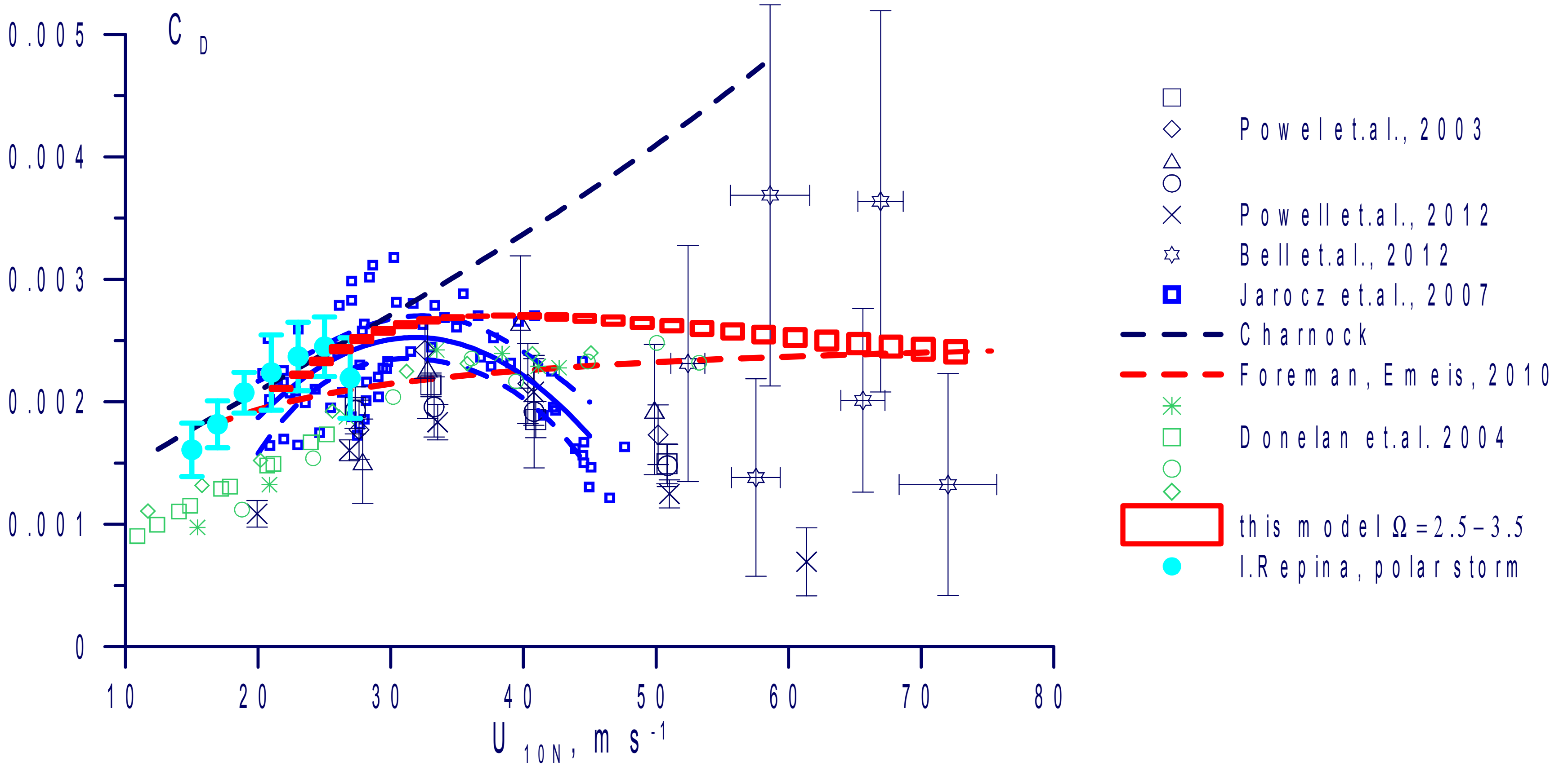


For neutral stratification of atmospheric boundary layer

Effect of spray on transfer coefficients

Sea surface drag via wind speed (hurricane)

$$F_M = F_{Mwaves} + F_{Mbags} + F_{Mspray}; C_{D10} = F_M / \rho_a U_{10}^2$$



Taking into account the effect of suspended droplets on the static stability of atmospheric boundary layer

Effect of the "bag-breakup" on air-sea fluxes.

Effect on air-sea moist enthalpy flux.

The spay enthalpy flux is a sensible heat flux driven by the temperature difference between the sea surface and the re-entered spray (Andreas, Emanuel, 2001)

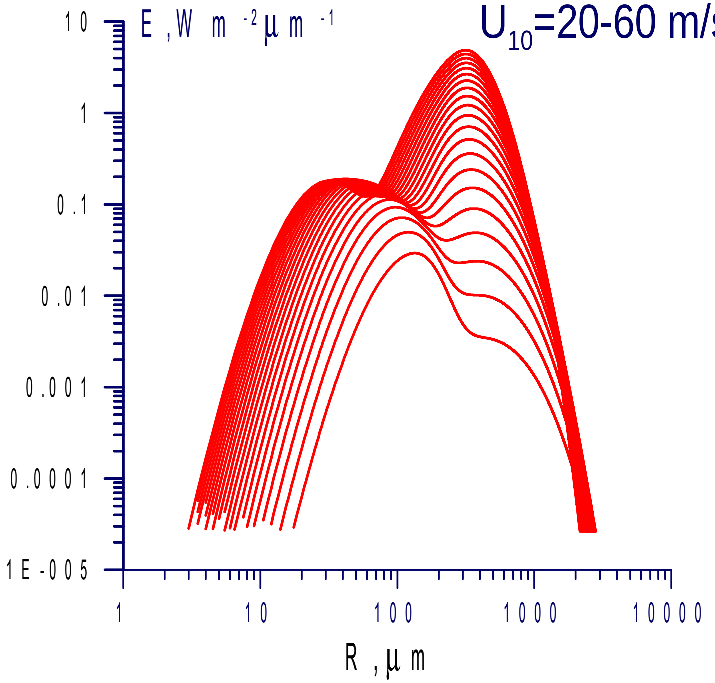
$$F_{QSpray} = \rho_w \int_0^{\infty} \frac{dF(r, u_*)}{dr} \frac{4\pi r^3}{3} Q_S dr$$

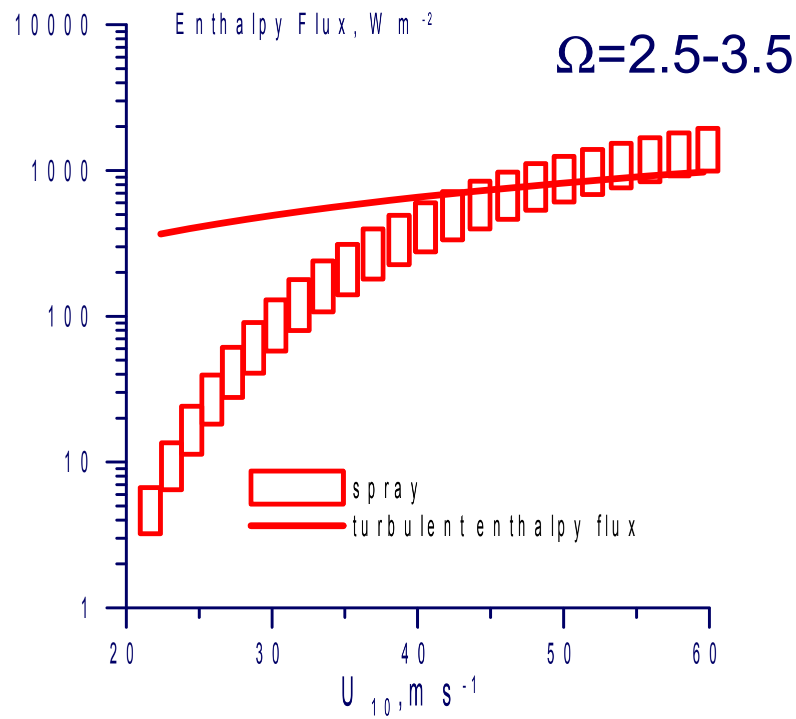
Sea spray microphysics by Andreas et al, 1989-2005

Sensible heat flux from one droplet

$$Q_S(r_0) = \rho_w C_{pw} (T_w - T_{eq}) (1 - \exp(-\tau_f / \tau_T))$$

Contribution of droplets to enthalpy flux, U_{10}=20-60 m/s



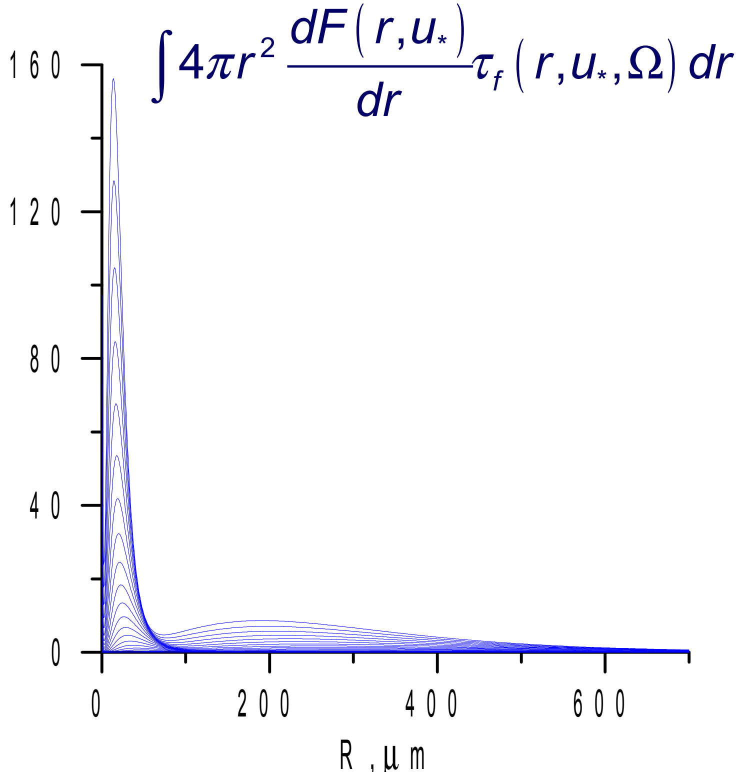


Estimate of contribution of spray to gas exchange at strong wind

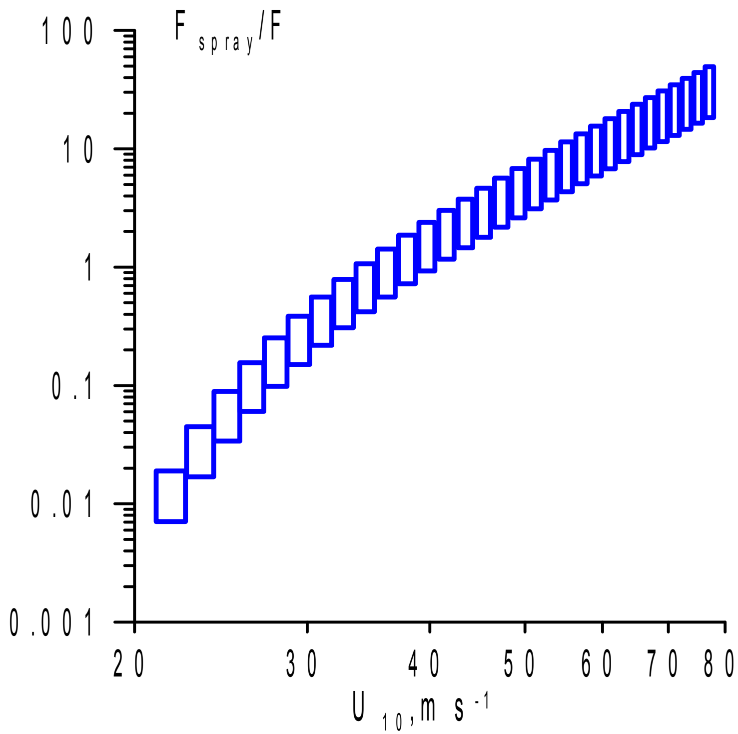
$$F_{spray} = F\int 4\pi r^2 \frac{dF\left(r,u_*\right)}{dr}\tau_f\left(r,u_*,\Omega\right)dr$$

F **is the direct gas flux from the unit area of unbroken surface, τ_f is the time of the spray residence in MABL (Andreas, 2005).**

Contribution of spray



The shear of gas fluxes from the surface and due to spray



Conclusions

- Statistical analyses of sequences of frames of high-speed video has enabled us to prove that the dominant spray-generation mechanism in extreme winds relates to the bag-breakup fluid fragmentation regime. It activates at conditions corresponding to Force 8 wind, manifested as “spindrift”.
- Starting from general principles of statistical physics, we develop statistics of the bag-breakup events and determine the spray generation function, which is in good agreement with available experimental data
- Giant droplets generated by bag-breakup significantly contribute to enthalpy and momentum flux:
  - 1) They significantly increase the air-sea enthalpy flux at hurricane wind
  - 2) They enables to explain non-monotonous dependence of surface drag coefficient on wind speed peaking at 35-40 m/s.
- Spray can be the main contributor to gas exchange at storms

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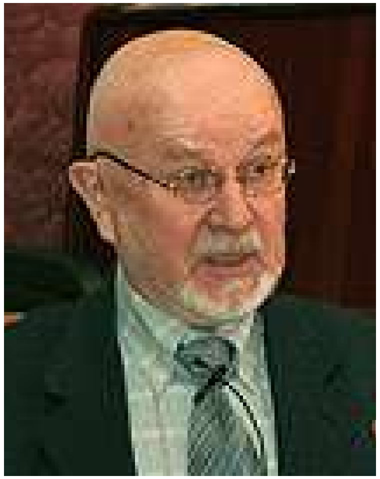

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