Численное моделирование процессов обмена между каплями и воздухом в приводном атмосферном погранслое

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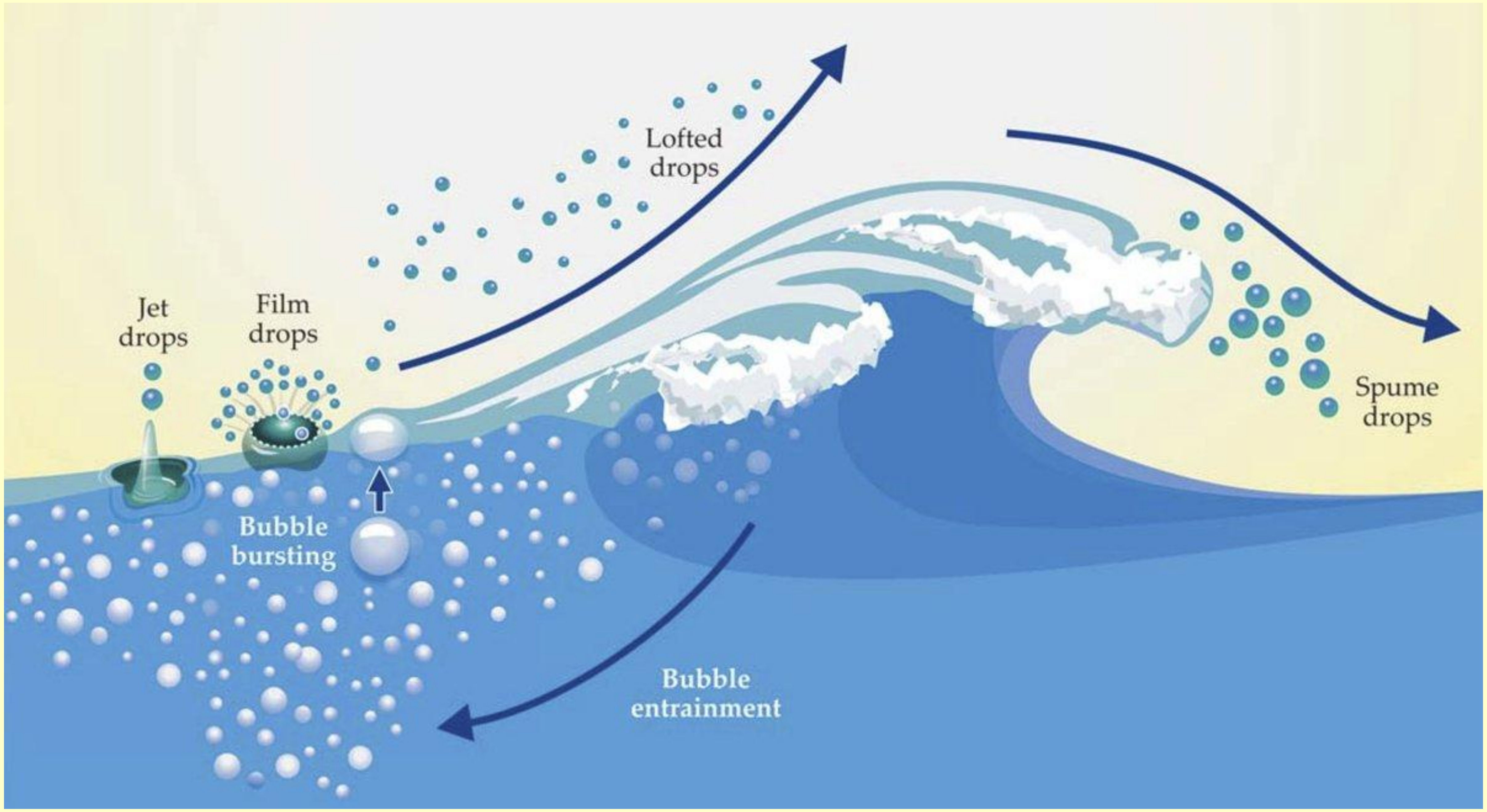
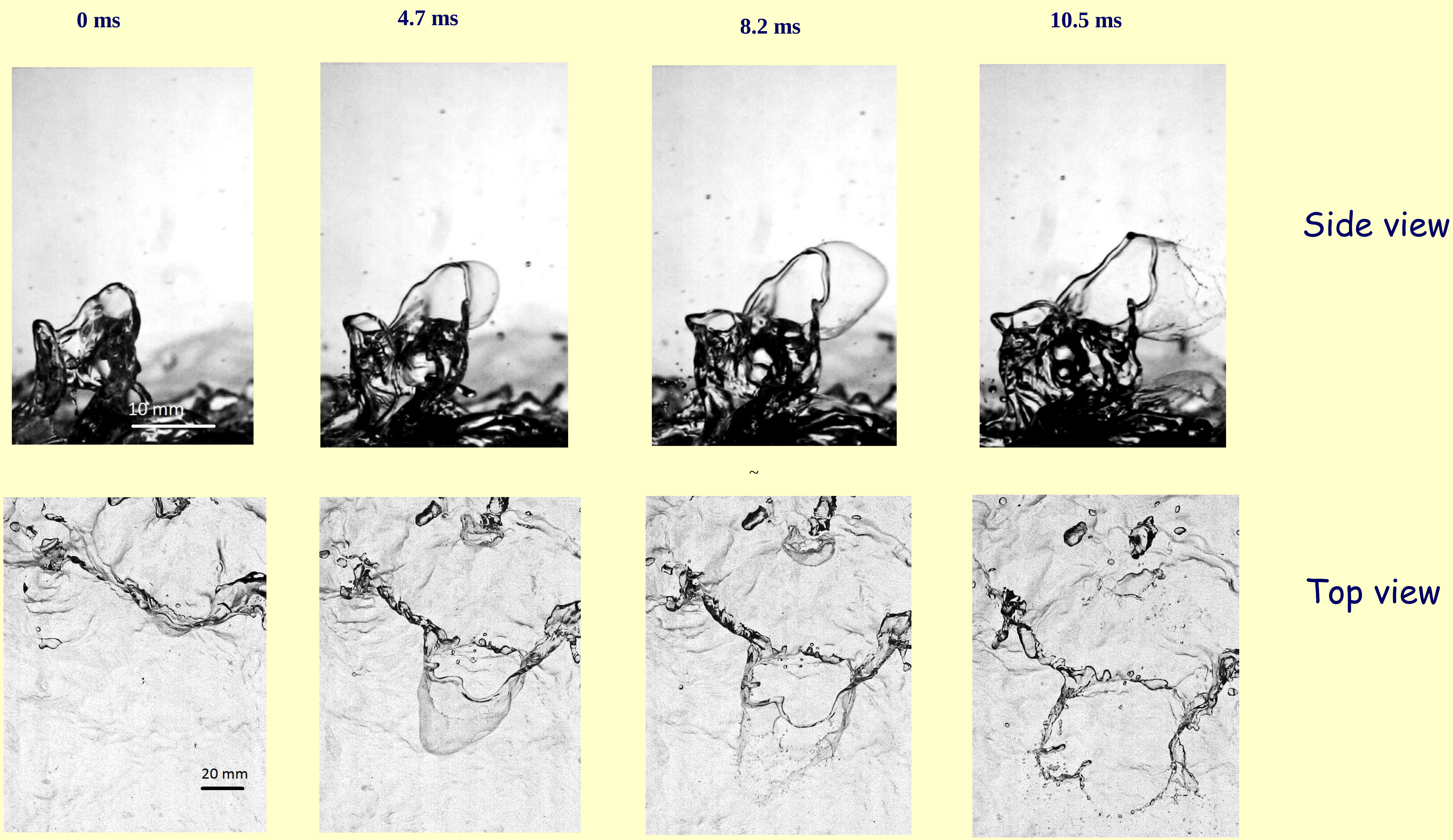
Sea surface at strong wind-forcing conditions

Drops injection schematic

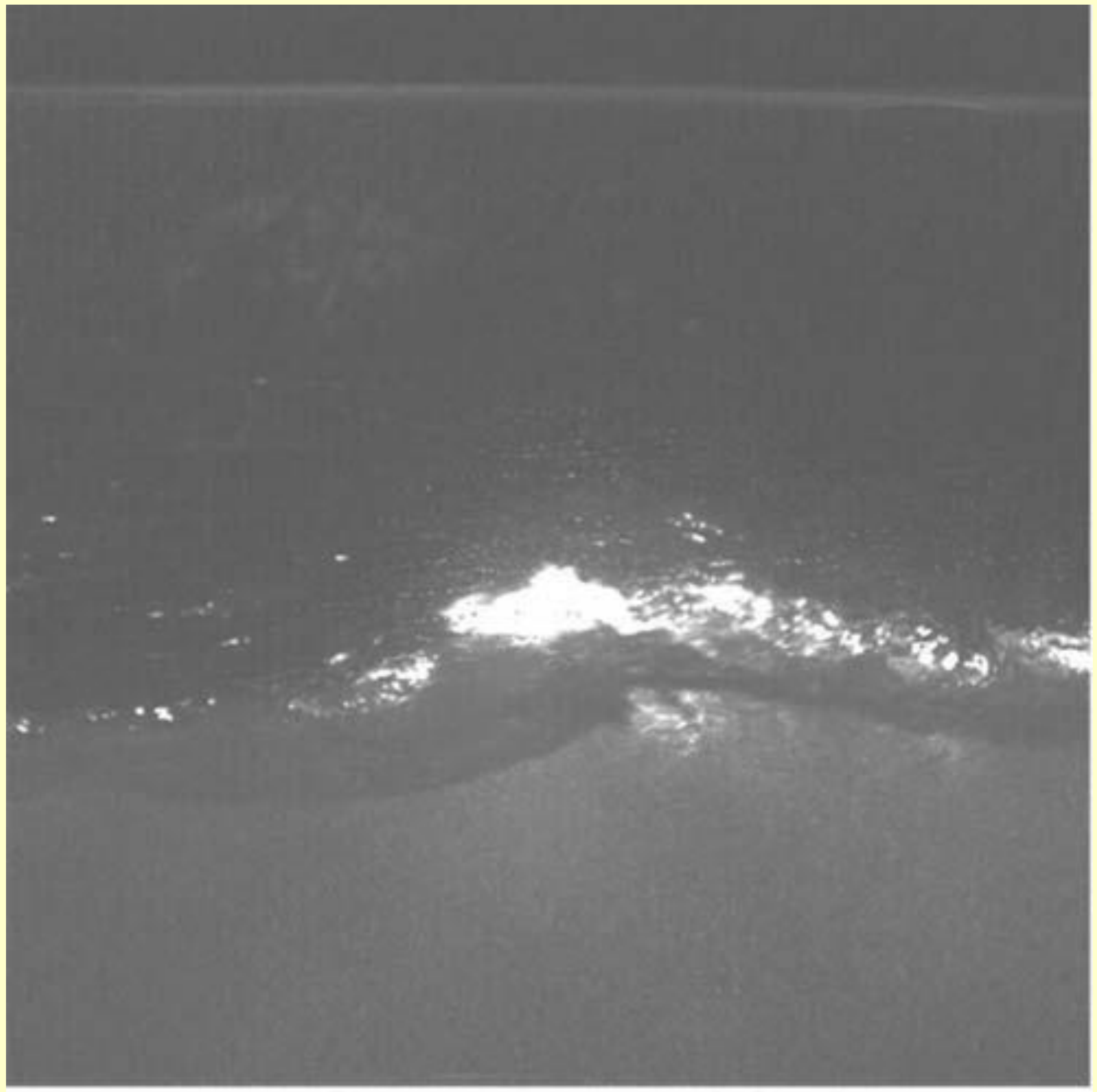


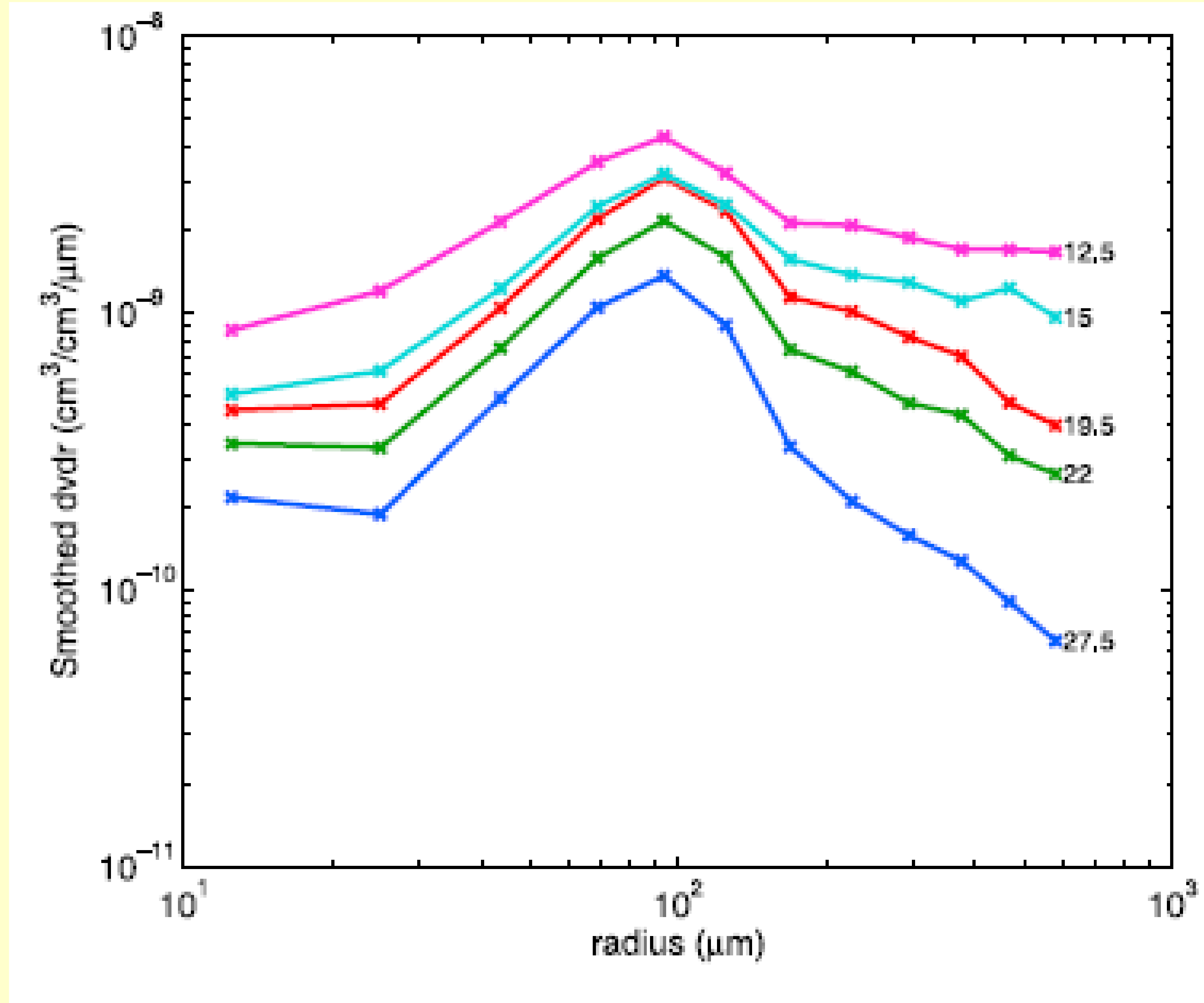
IAP RAS Lab experiment (Troitskayal et al.,2017)



Formation of spume drops at the water surface at wind speed about 25 m/s captured by high-speed video recording

Lab experiment (Fairall et al.,2009 JGR)

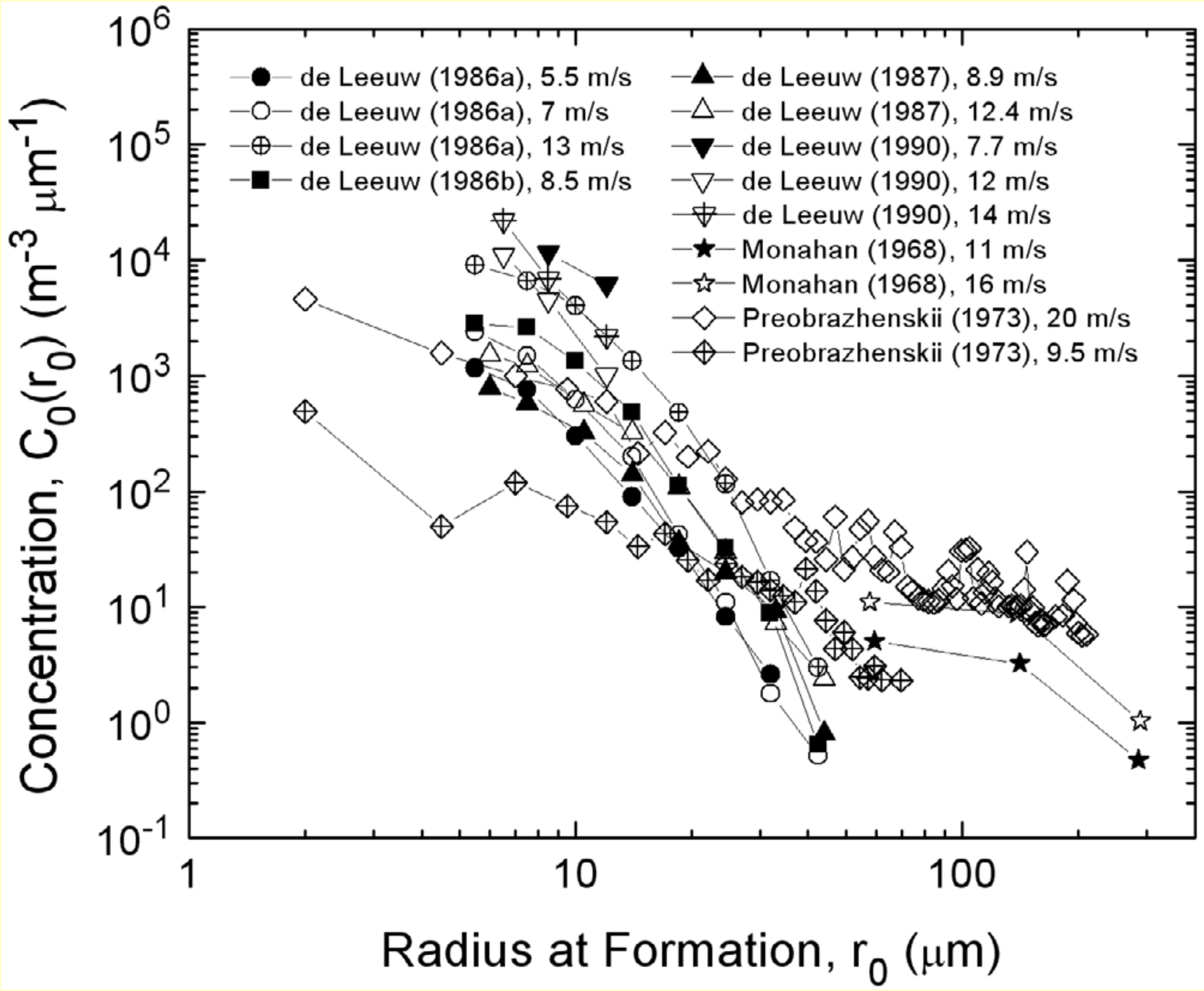




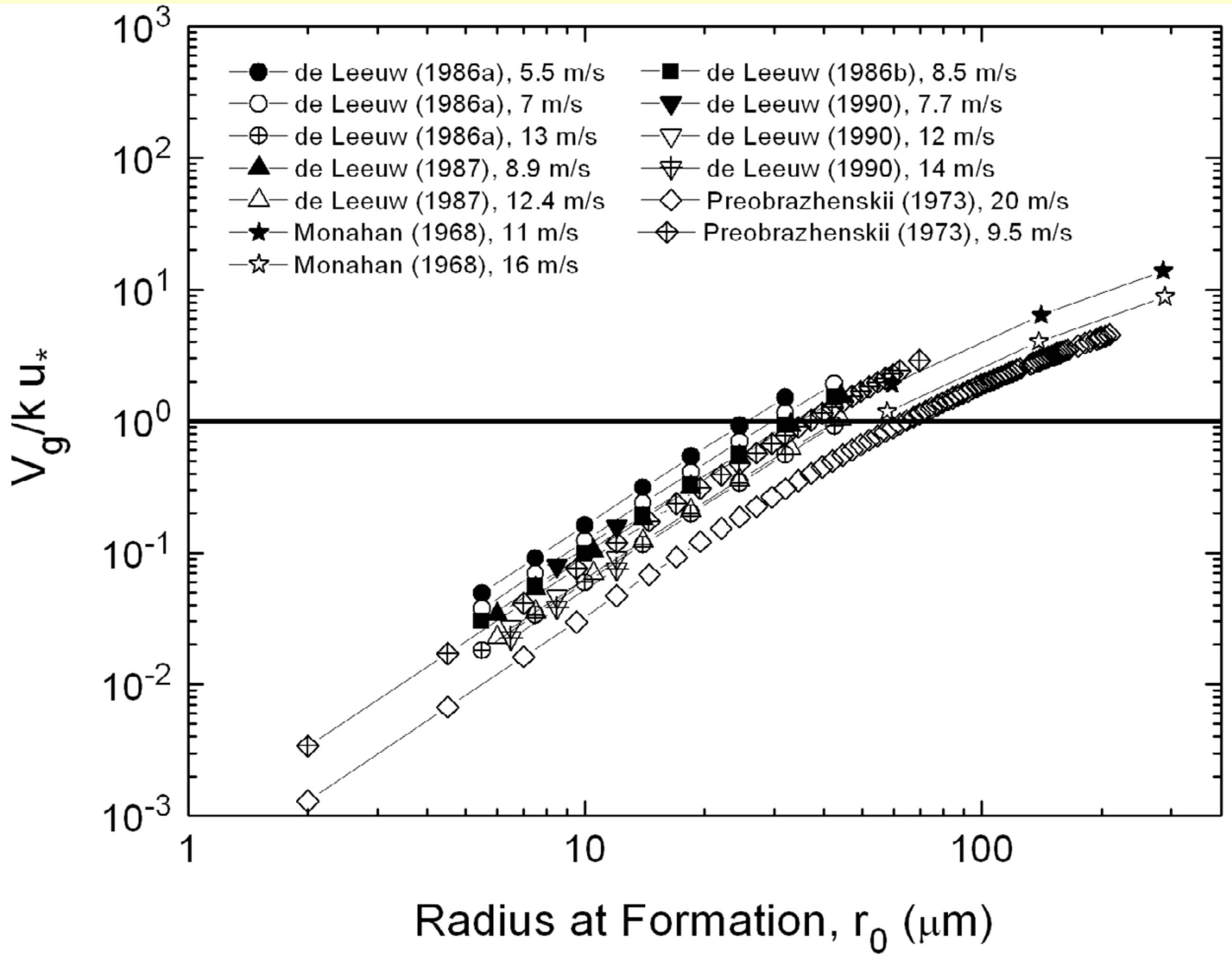
Typical high-speed video image showing spray droplets shed by a breaking wave, captured at 200 Hz.

Droplet volume concentration for wind speed 16m/s at different heights above the water surface (in cm)

Data on droplets generation by the wind (Andreas et al. 2010, JGR)



Droplet number density at different wind speeds at heights from 1 to 2m.



Droplet terminal velocity normalized by friction velocity and Karman constant (k=0.4)

$$\left(V_g = g\frac{d^2}{18\nu}\frac{\rho_w}{\rho_a} \right)$$

Heat and moisture exchange between air and sea-spray drops (Andreas et al. 2015)

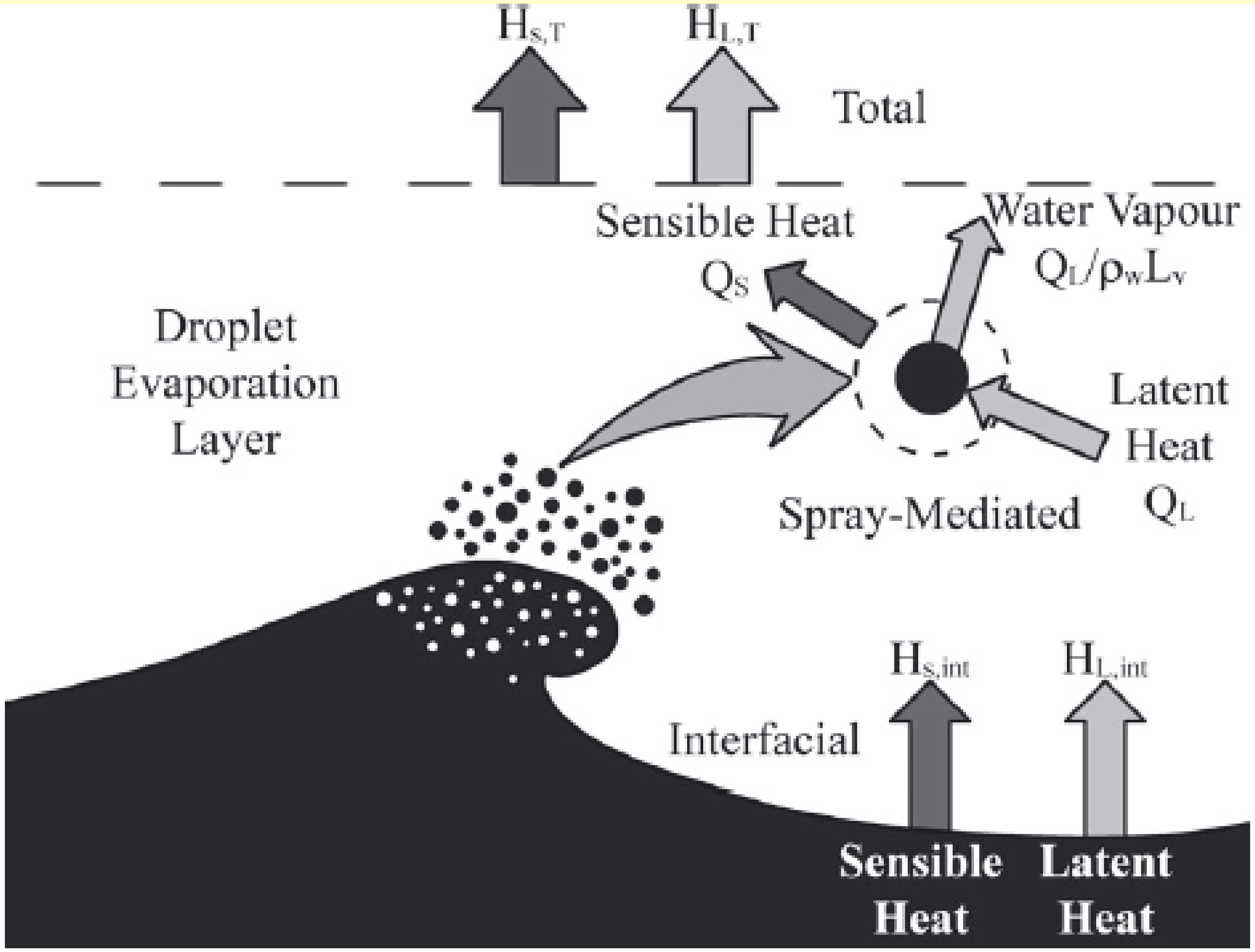


Figure 1. Processes in the droplet evaporation layer. Air and sea are always exchanging sensible ($H_{s,int}$) and latent ($H_{L,int}$) heat right at the interface. Both fluxes can go in either direction, depending on the local air–sea temperature and humidity differences. The labelled circles depict an individual spray droplet. This droplet cools rapidly, thereby giving up sensible heat. Its evaporation yields water vapour but extracts latent heat from the air. Q_L and Q_S are the latent and sensible heat fluxes associated with this single droplet. The interfacial and spray fluxes combine to give the total sensible ($H_{s,T}$) and latent ($H_{L,T}$) heat fluxes coming out of the top of the droplet evaporation layer.

Filed experiment during typhoons "Skip" and "Tess" (1988): cooling of the air boundary flow

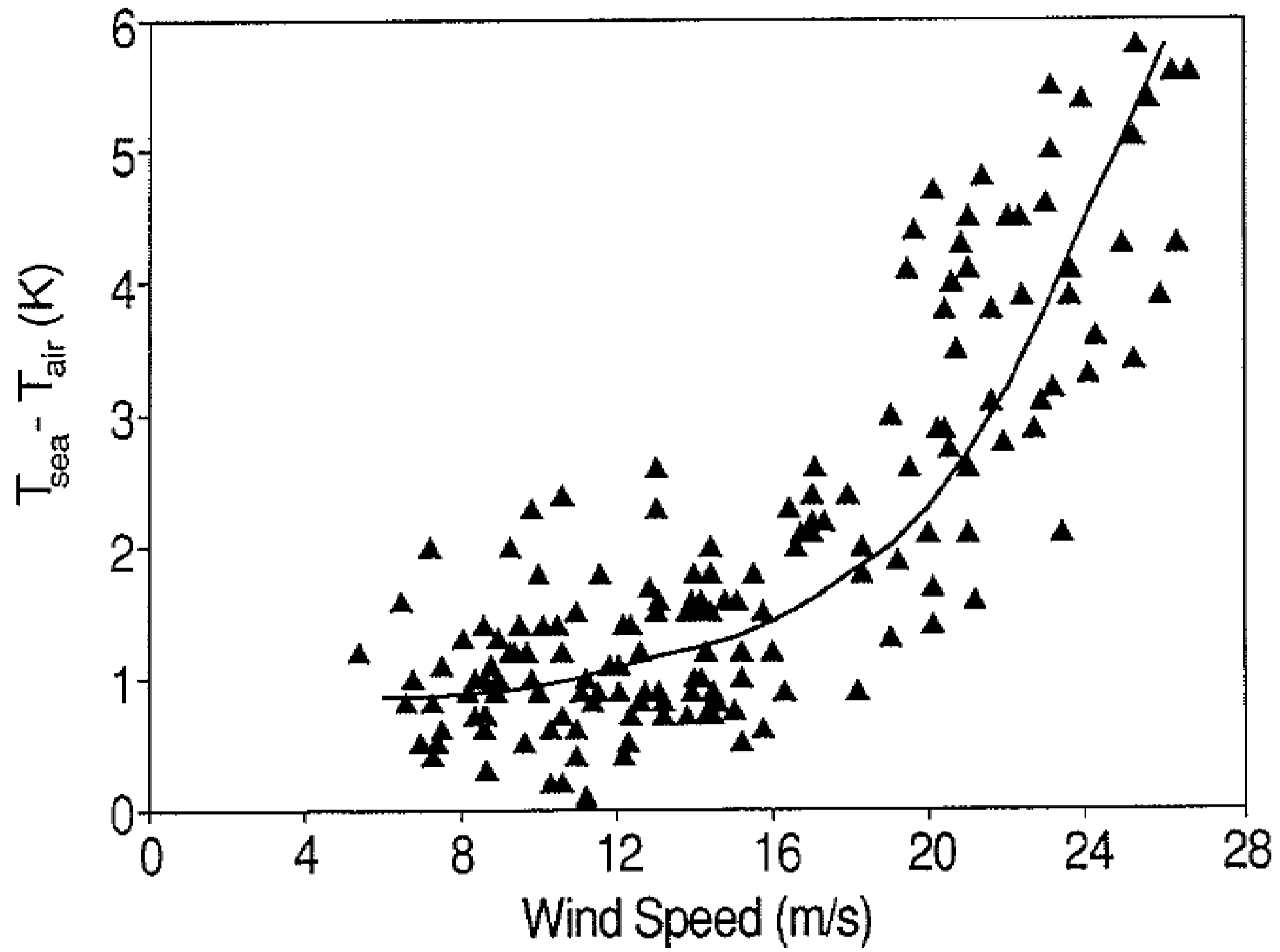


FIGURE 2 The marine boundary layer cooling associated with strong winds in two tropical cyclones, shown as a scatter diagram of observed air-sea temperature difference plotted against wind speed (Pudov, personal communication, 1991).

Phenomenological models

(Fairall et al. 1994, Kudryavtsev & Makin 2011): consider Reynolds – averaged (RANS) equations where the impact of drops on the air mometum, temperature and humidity is modeled by source terms obtained by phenomenological closure assumptions.

Lagrangian stochastic models

Edson & Fairall (1994), Mueller & Veron (2014), Troitskaya et al. (2016): numerical simulation of the dynamics of individual drops in a prescribed mean air flow field and turbulent fluctuations of the surrounding air fields modeled by an artificial stochastic component.

Direct numerical simulation

Druzhinin et al. (2017): DNS of turbulent particle-laden Couette flow laden with monodisperse drops over waved water surface. Only momentum exchange between air and drops taken into account, but not the heat exchange and drops evaporation effects.

OBJECTIVE

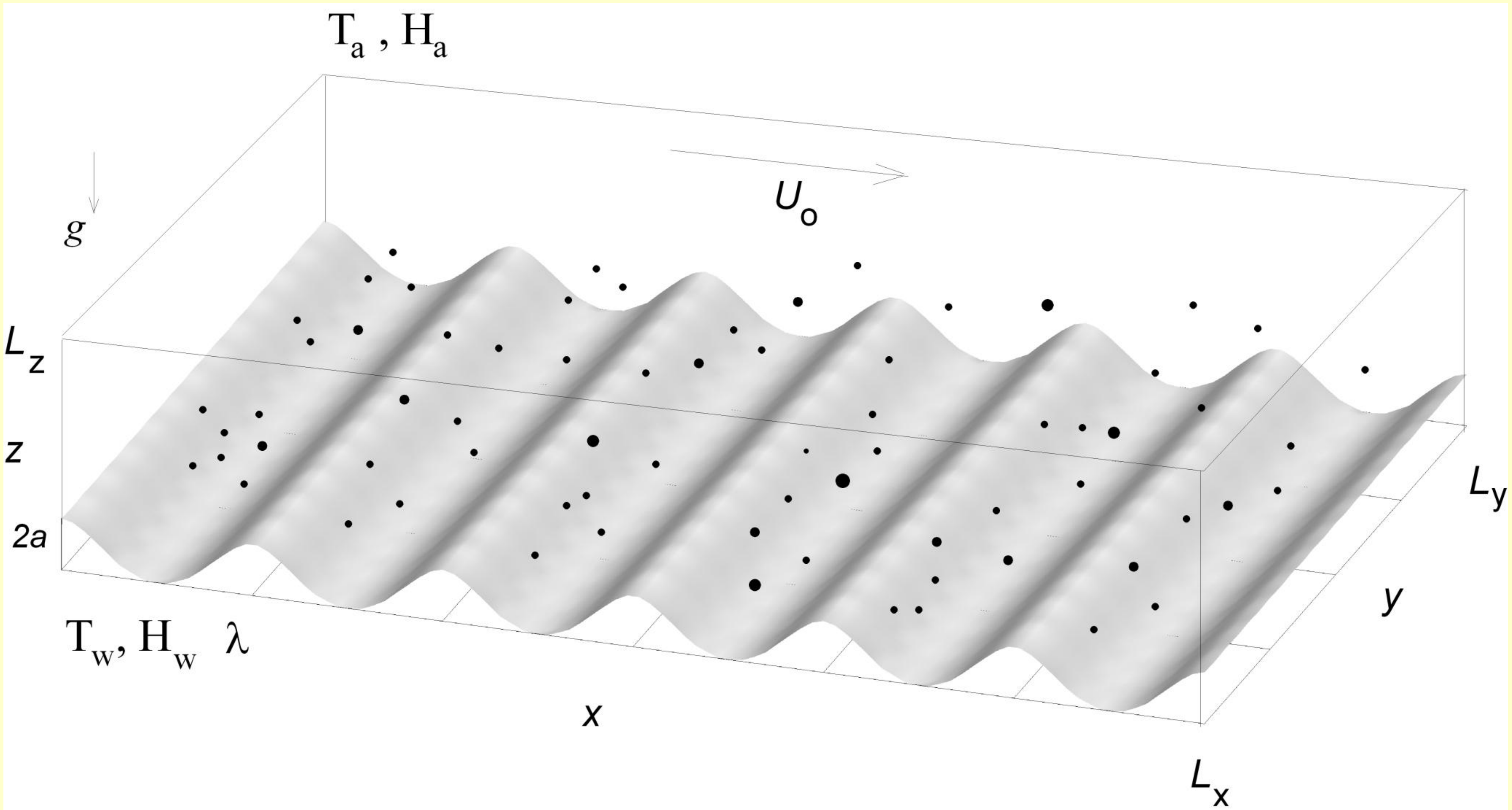
To perform DNS of a turbulent, droplet-laden air flow over waved water surface taking into account momentum, heat and moisture exhange between air and drops.

3D Navier-Stokes equations for the air including the impact of discrete drops and the equations of motion of individual drops are solved simultaneously in curvilinear coordinates in a frame of reference moving the phase velocity of the wave.

Two-dimensional water wave with wave slope up to ka = 0.2 is considered. The shape of the water wave is prescribed and does not evolve under the action of the wind and/or drops.

Droplet mass concentration 0.03 is attained (up to 12×10^6 drops with diameter from O(10 μm) to O(100μm) are considered) to get a significant impact of drops on the air flow.

Schematic of numerical experiment



T-temperature
H-humidity
U_0- air bulk velocity

c/U_0=0.05 – wave celerity
ka =0.2 – maximum wave slope

Domain sizes: $L_x = 6\lambda \quad L_y = 4\lambda \quad L_z = \lambda$

$$\mathrm{Re} = \frac{U_0 \lambda}{\nu} = 15000$$ - bulk Reynolds number

Tropical cyclon conditions: T_a=27^{0}C, T_w=28^{0}C , H_w=98%, H_a=80%
Polar low conditions: T_a=-20^{0}C, T_w=0^{0}C , H_w=98%, H_a=70%

GOVERNING EQUATIONS: AIR FLOW
Eulerian framework

Momentum

$$\frac{\partial U_i}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho_a}\frac{\partial P}{\partial x_j} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} + \delta_{iz} g \frac{T}{T_a} + \sum_{n=1}^{N_d} f_{Ui}^n$$

Continuity

$$\frac{\partial U_j}{\partial x_j} = 0$$

Temperature

$$\frac{\partial T}{\partial t} + \frac{\partial (TU_j)}{\partial x_j} + \frac{\partial (T_{ref} U_3)}{\partial x_3} = \kappa \frac{\partial^2 T}{\partial x_j \partial x_j} + \sum_{n=1}^{N_d} f_T^n$$

Humidity

$$\frac{\partial H}{\partial t} + \frac{\partial (HU_j)}{\partial x_j} + \frac{\partial (H_{ref} U_3)}{\partial x_3} = D \frac{\partial^2 H}{\partial x_j \partial x_j} + \sum_{n=1}^{N_d} f_H^n$$

Drops feedback contributions

N_d = const –total number of drops in DNS

$$T_{ref}(z) = T_w + (T_a - T_w)\frac{z}{\lambda}$$

$$H_{ref}(z) = H_w + (H_a - H_w)\frac{z}{\lambda}$$

- reference profiles

d_n

GOVERNING EQUATIONS: DROPS
Lagrangian framework

coordinate
$$\frac{dr_i^n}{dt} = V_i^n$$

velocity
$$\frac{dV_i^n}{dt} = \frac{1}{\tau_n}\left(U_i(r^n) - V_i^n\right)\left(1 + 0.15\,\mathrm{Re}_n^{0.687}\right) - \delta_{iz} g$$

temperature
$$m_n c_w \frac{dT_n}{dt} = 2\pi\kappa' d_n \left(T_a(r^n) - T_n\right)\left(1 + 0.25\,\mathrm{Re}_n^{0.5}\right) + L_v \frac{dm_n}{dt}$$

mass
$$\frac{dm_n}{dt} = 2\pi D' d_n \rho_{sat}^v \left(H(r^n) - H_n^s\right)\left(1 + 0.25\,\mathrm{Re}_n^{0.5}\right)$$

$$\mathrm{Re}_n = \frac{|U(r^n) - V^n|\, d_n}{\nu}$$ - drop Reynolds number

$$\tau_n = \frac{d_n^2}{18\nu}\frac{\rho_n}{\rho_a}$$ - response time

D' - diffusivity of water vapor

κ' -thermal conductivity coefficient of air

d_n - diameter

$m_n = \rho_n \pi d_n^3 / 6$ - mass

ρ_{sat}^v - saturated vapor density

H_n^s Humidity at the drop surface

L_v - latent heat of evaporation

c_w - specific heat of water

Air velocity, humidity and temperature at each drop location are obtained by Hermitian polynomial interpolation

Feed-back contributions due to drops

Momentum
$$f_{Ui}^n = \frac{\pi d_n^3}{6}\frac{\rho_d^n}{\rho_a}\frac{1}{\tau_n}\left(V_i^n - U_i(r^n)\right)\left(1 + 0.15\,\mathrm{Re}_n^{0.687}\right)\frac{w(r^n, r)}{\Omega_g}$$

Temperature
$$f_T^n = 2\pi\kappa' d_n\left(T_n - T_a(r^n)\right)\left(1 + 0.25\,\mathrm{Re}_n^{0.25}\right)\frac{1}{\rho_a c_a}\frac{w(r^n, r)}{\Omega_g}$$

Humidity
$$f_H^n = -\frac{1}{\rho_{sat}^v}\frac{dm_n}{dt}\frac{w(r^n, r)}{\Omega_g}$$

$$\mathrm{Re}_n = \frac{|U(r^n) - V^n|\, d_n}{\nu}$$ - drop Reynolds number

r^n - drop coordinate

r- grid node coordinate

$w(r^m, r)$ - geometrical weighting factor

$\Omega_g(r)$ – grid cell volume

POINT-FORCE APPROXIMATION is used:
Each drop is considered as a point, and its feedback contributions to the momentum, heat and moisture of the air flow are distributed to the surrounding grid nodes.

CURVILINEAR COORDINATES

$$x = \xi - a\exp(-k\eta)\sin k\xi$$

$$z = \eta + a\exp(-k\eta)\cos k\xi$$

Shape of the water surface: $z_b(x) = a\cos kx + \frac{1}{2}a^2k(\cos 2kx - 1)$

Mapping over η: $\eta = 0.5\left(1 + \frac{\tanh\tilde{\eta}}{\tanh 1.5}\right)$ $\quad -1.5 < \tilde{\eta} < 1.5$

Grid of 360 x 240 x 180 nodes is employed with mesh sizes:

$\Delta x^+ \approx 6$ in the horizontal direction

$\Delta z_1^+ \approx 0.3$ near water surface in the vertical direction

$\Delta z_2^+ \approx 3$ in the middle of the domain

BOUNDARY CONDITIONS

Air velocity = water velocity in the surface wave:

$$U(\xi, y, 0) = c\left(ka\cos kx(\xi,\eta) - 1\right)$$

$$V(\xi, y, 0) = 0$$

$$W(\xi, y, 0) = cka\sin kx(\xi,\eta)$$

No-slip condition at the upper moving plane :

$$U(\xi, y, 1) = 1 - c$$

$$V(\xi, y, 1) = 0$$

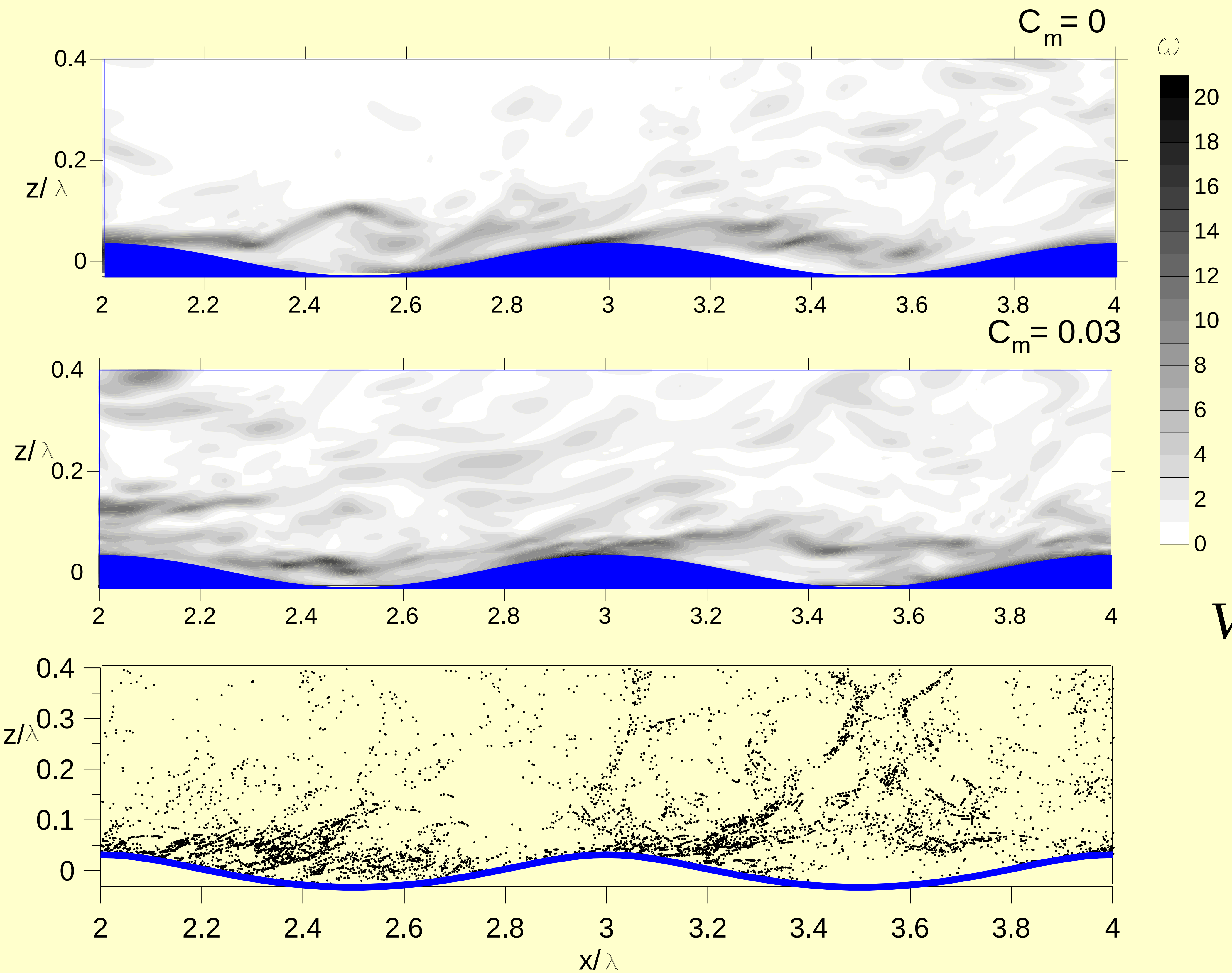
$$W(\xi, y, 1) = 0$$

Deviations of temperature and humidity from reference profiles at top and bottom boundaries are put to zero.

All fields are x and y periodic

Instantaneous vorticity modulus and drops coordinates fields: side view at y=0

no drops



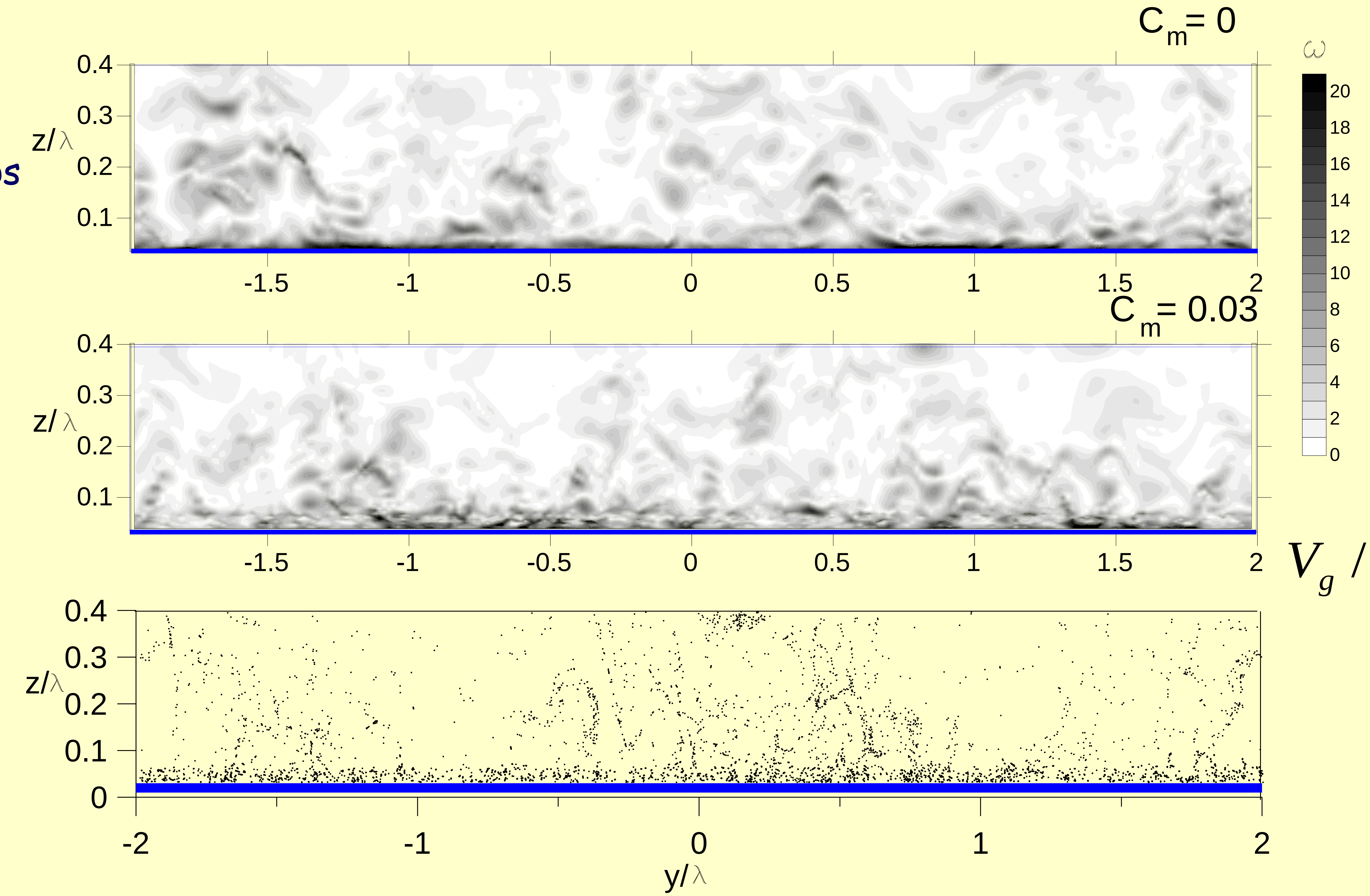
$ka = 0.2$

$V_g / \kappa u_* \approx 1$

$$\left(V_g = g \frac{d^2}{18\nu} \frac{\rho_w}{\rho_a} \right)$$ - drop terminal velocity; κ =0.4; u_* - friction velocity

Instantaneous vorticity modulus and drops coordinates fields: front view at x=3λ

no drops



$ka = 0.2$

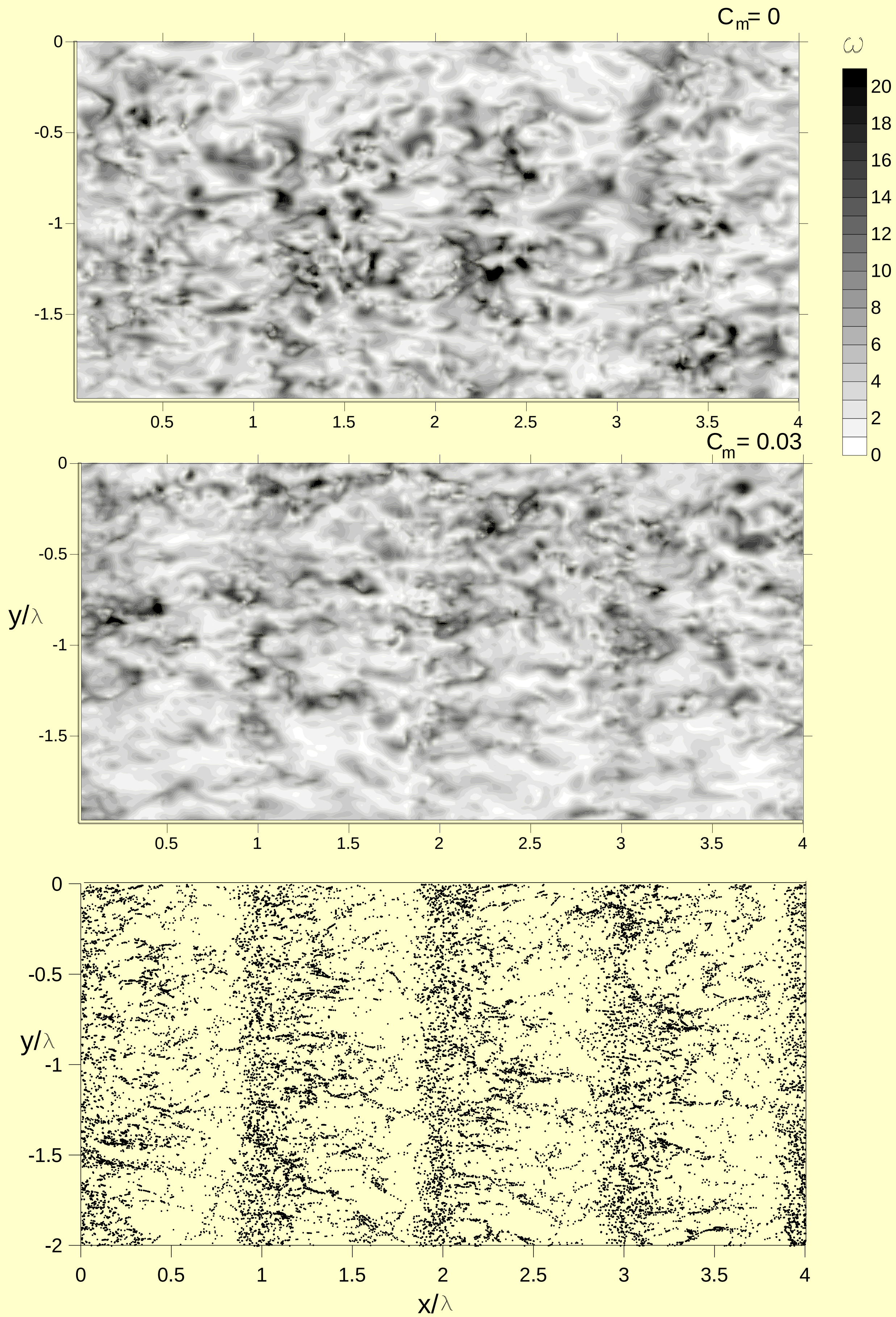
$V_g / \kappa u_* \approx 1$

Instantaneous vorticity modulus and drops coordinates fields: top view at $z/\lambda = 0.04$ ($z^+=20$)

Vorticity modulus, no drops

Vorticity modulus, with drops

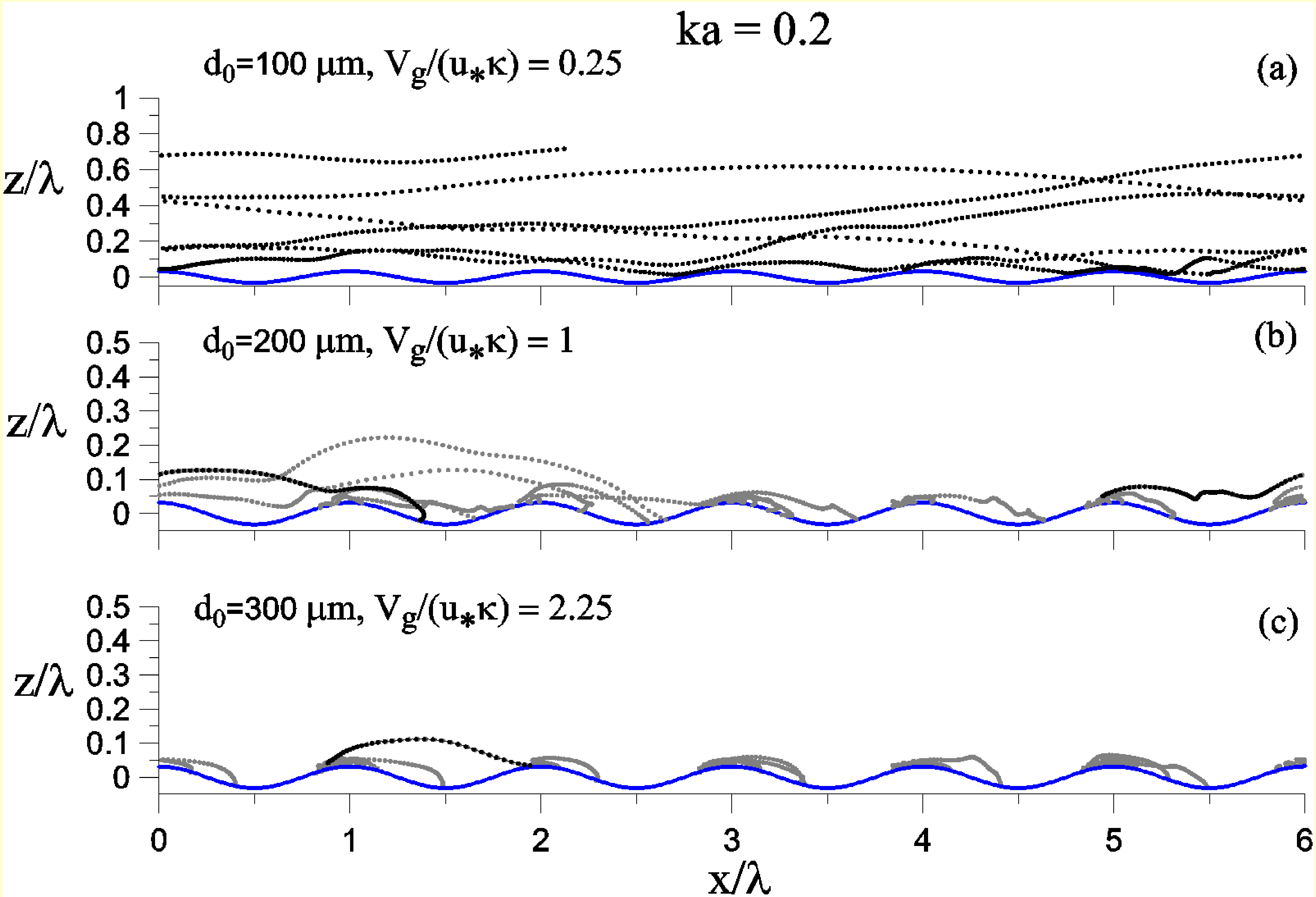
Drops locations



$$ka = 0.2$$

$$V_g / \kappa u_* \approx 1$$

Drops trajectories



Drops injection:

Drops falling on the water or reaching the upper plane are re-injected in the vicinity of the wave crests in the range:

$$0.01 < \eta / \lambda < 0.05 \quad (5 < \eta u_* / \nu < 25)$$

$$n\lambda - 0.2 < \xi < n\lambda \qquad n = 1, \ldots, 6$$

Drop velocity at injection = water surface velocity (Andreas 2004, Troitskaya et al. 2016) ; initial diameter is in the range

$$100\mu m \le d_0 \le 300\mu m$$

Drops temperature at injection = water temperature

Lagrangian dynamics of fluxes:

Rate of change of drop momentum

$$m_d \frac{dV_x^d}{dt} = -\rho_a f_x^d$$

Rate of change of drop temperature

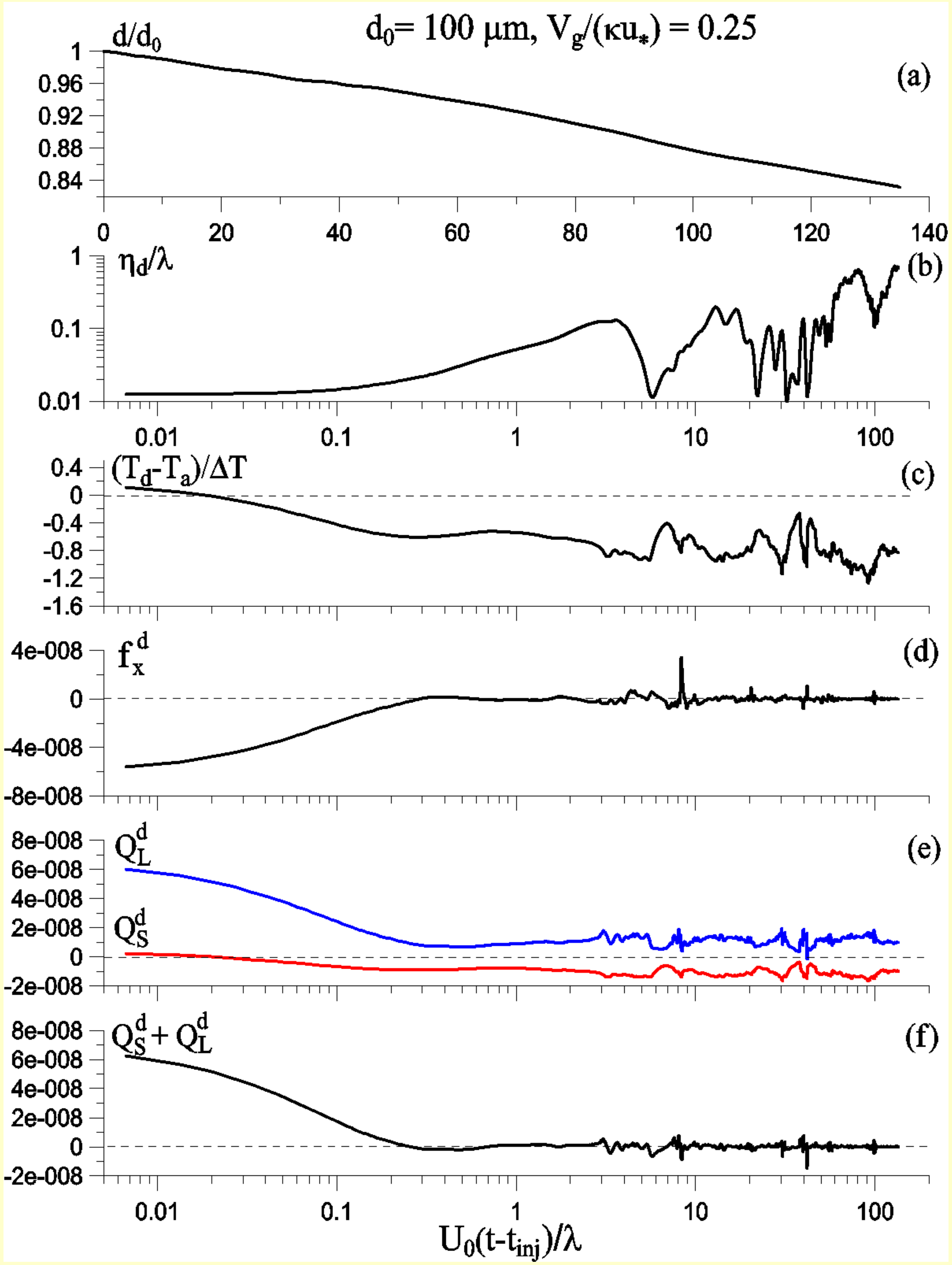
$$m_d c_w \frac{dT_d}{dt} = -Q_S^d - Q_L^d$$

$$f_x^d = 3\pi d \nu \left(V_x^d - U_x(r^d)\right)\left(1 + 0.15\,\mathrm{Re}_d^{0.687}\right)$$ - Momentum flux

$$Q_S^d = 2\pi\kappa' d\left(T_d - T_a(r^d)\right)\left(1 + 0.25\,\mathrm{Re}_d^{0.5}\right)$$ - Sensible heat flux

$$Q_L^d = -L_v \frac{dm_d}{dt}$$ - Latent heat flux

Drop trajectory for d_0=100 mμ



Diameter

Distance from water

Temperature
(relative to air)

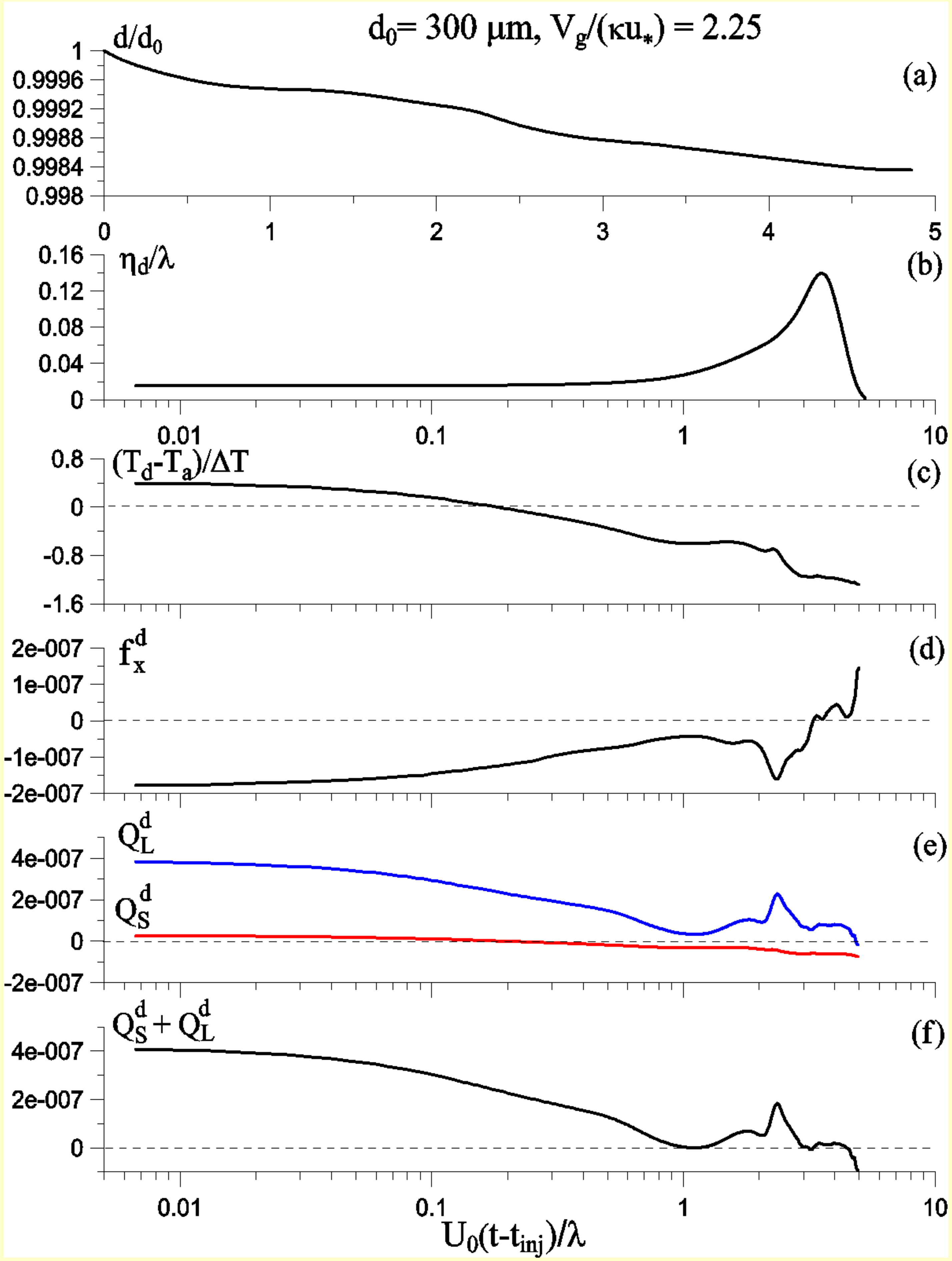
Momentum flux to the air

Latent and sensible heat flux

Enthalpy flux

$Q_S^d + Q_L^d \approx 0$ -"Wet bulb" state of the drop

Drop trajectory for d_0=300 mμ



Diameter

Distance from water

Temperature
(relative to air)

Momentum flux to the air

Latent and sensible heat flux

Enthalpy flux

d-distributions

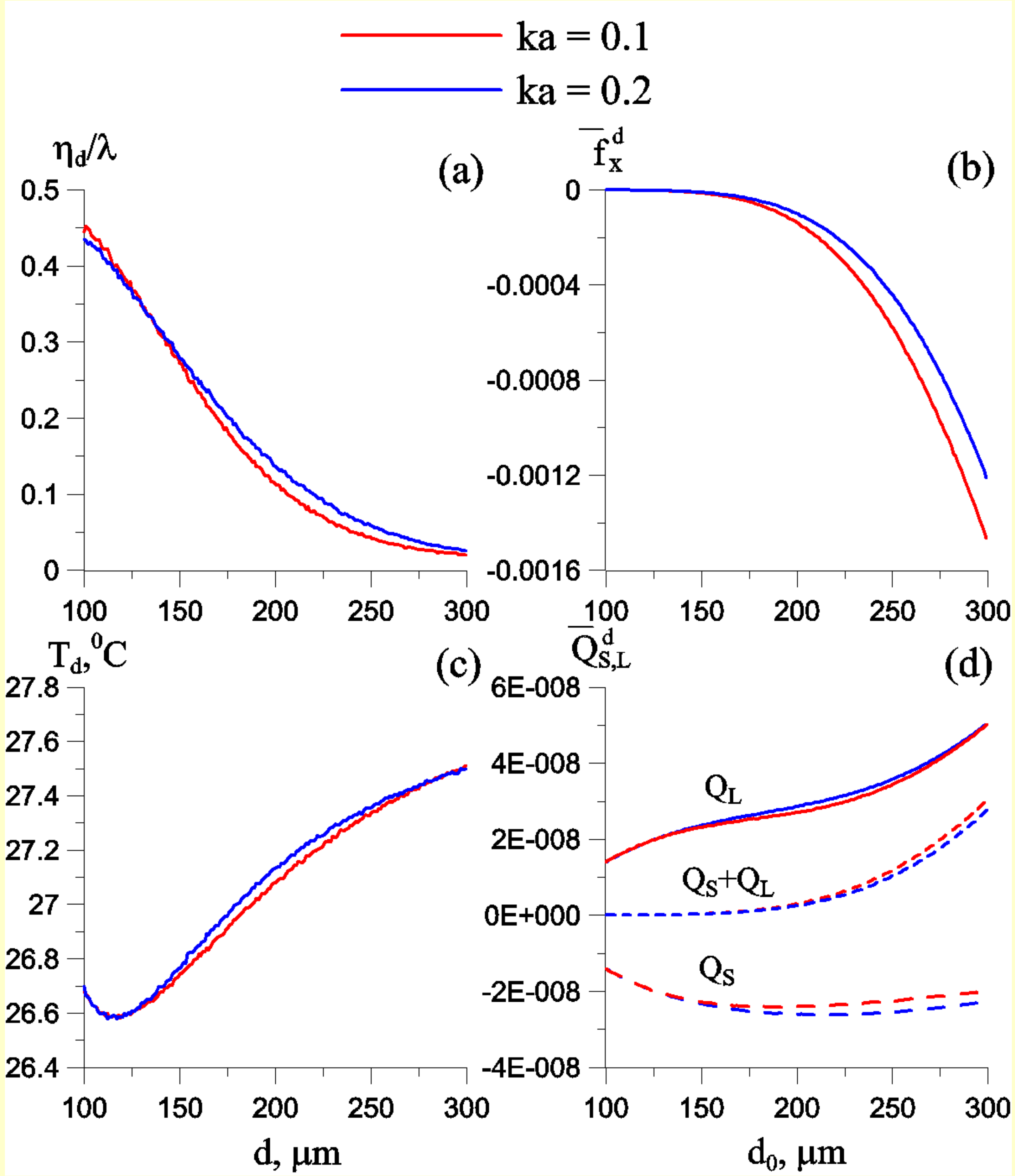
instantaneous time-averaged

Distance from drop to water

Momentum flux

Drop temperature

Sensible and latent heat and enthalpy fluxes



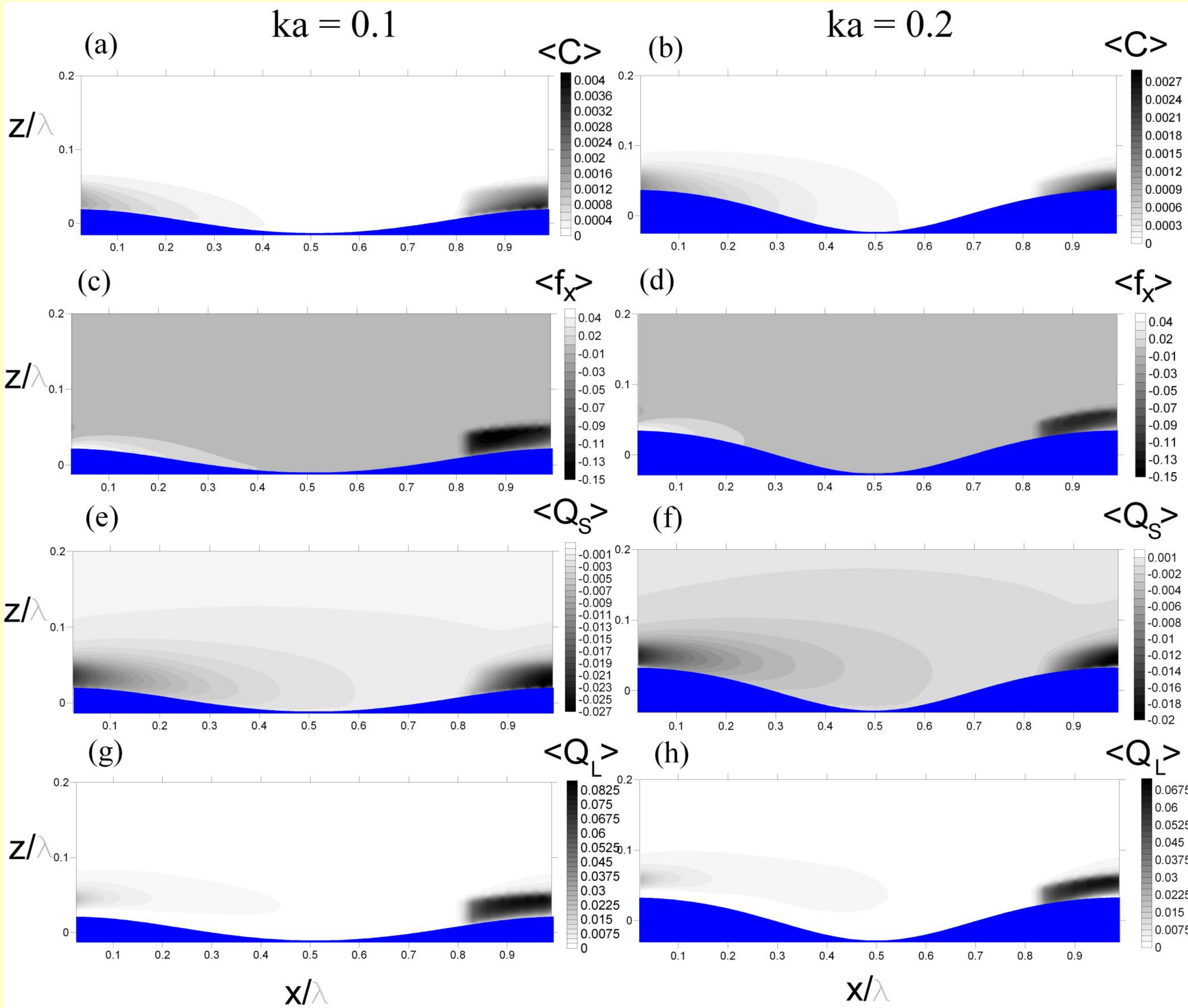
Phase (ensemble)-averaged fields

Drops volume fraction (concentration)

Momentum flux

Sensible heat flux

Latent heat flux



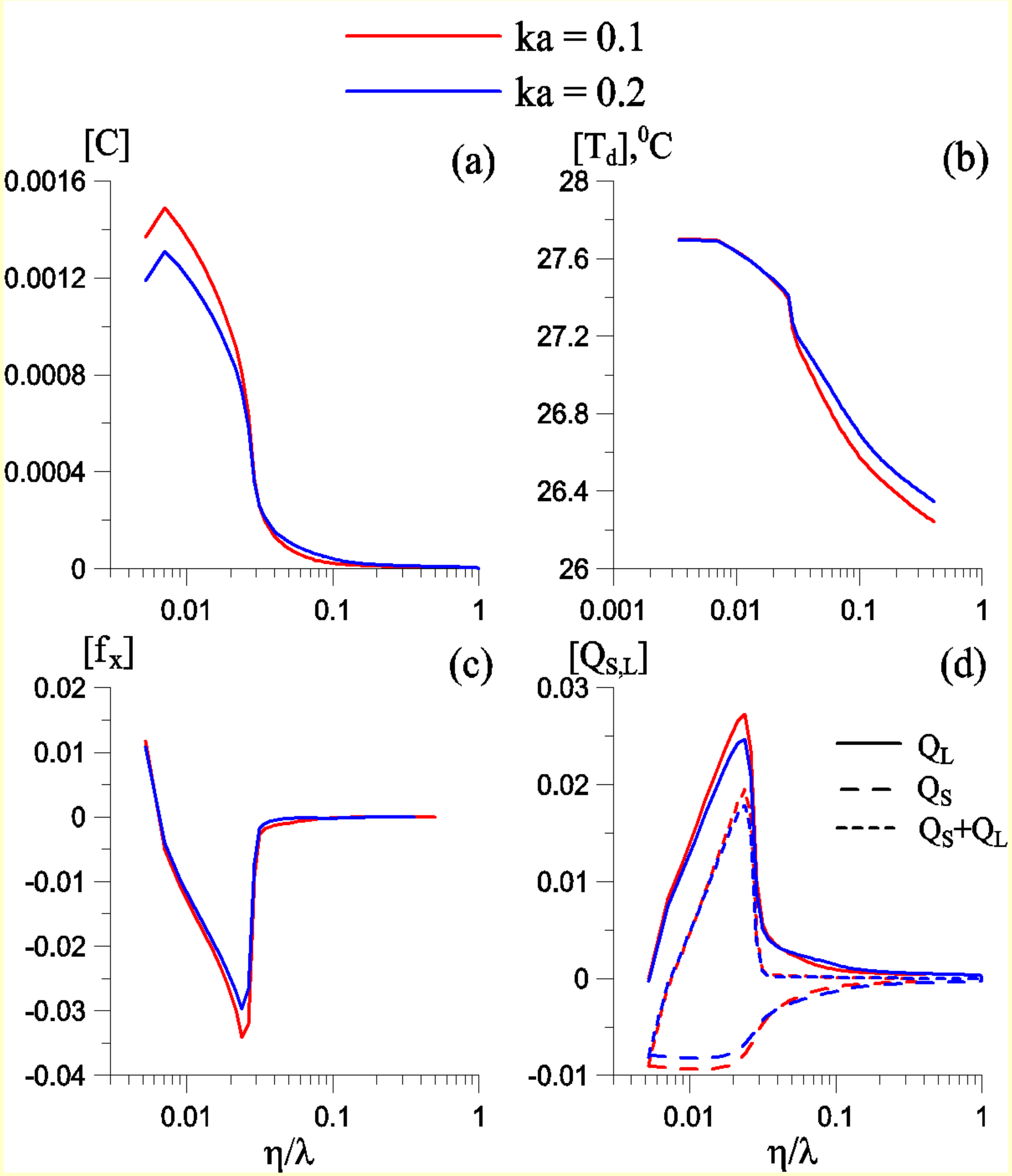
z(η)-profiles

Drops volume fraction

Drops temperature

Momentum flux

Sensible and Latent heat fluxes

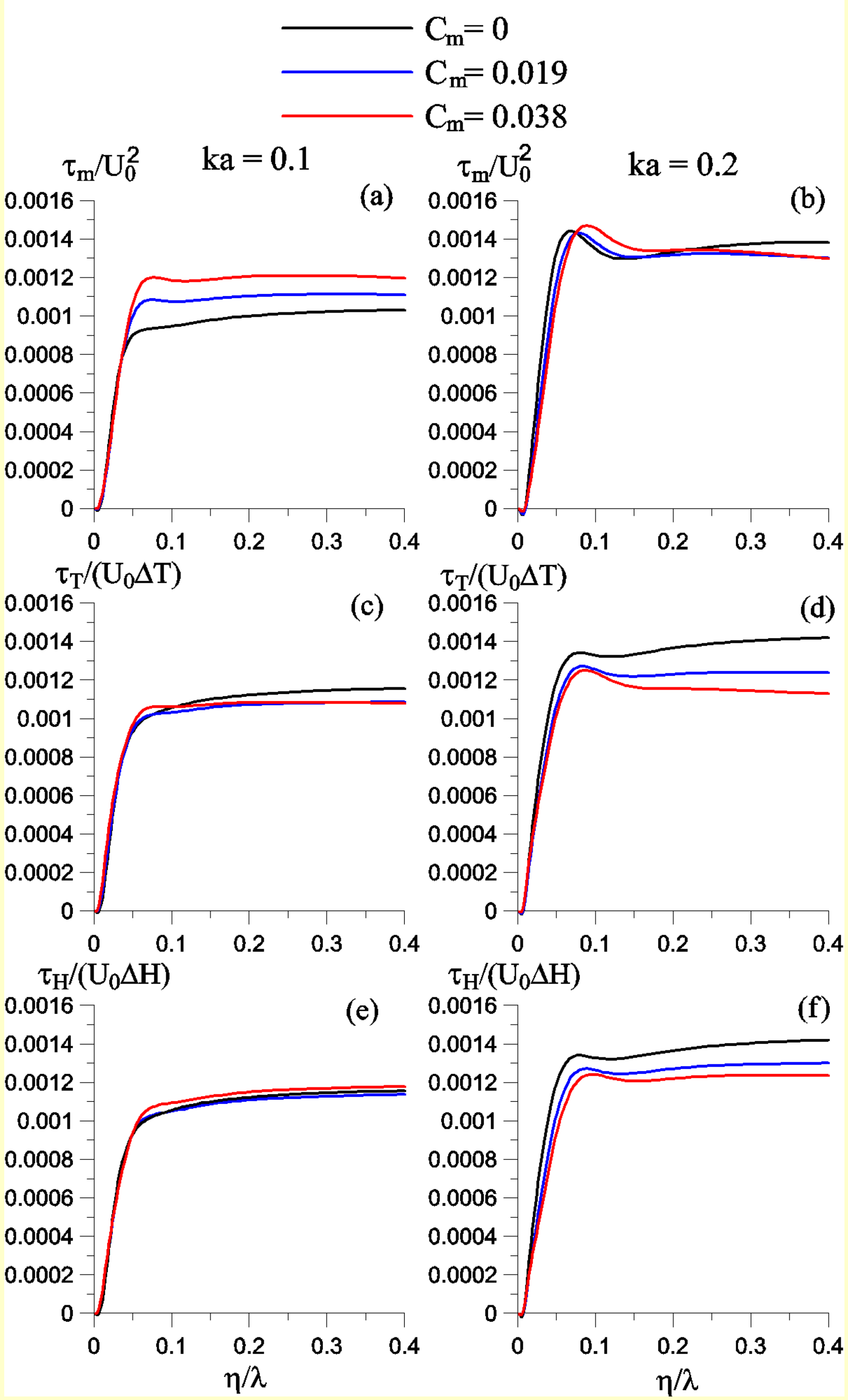


Turbulent fluxes

Momentum

Sensible heat

Humidity

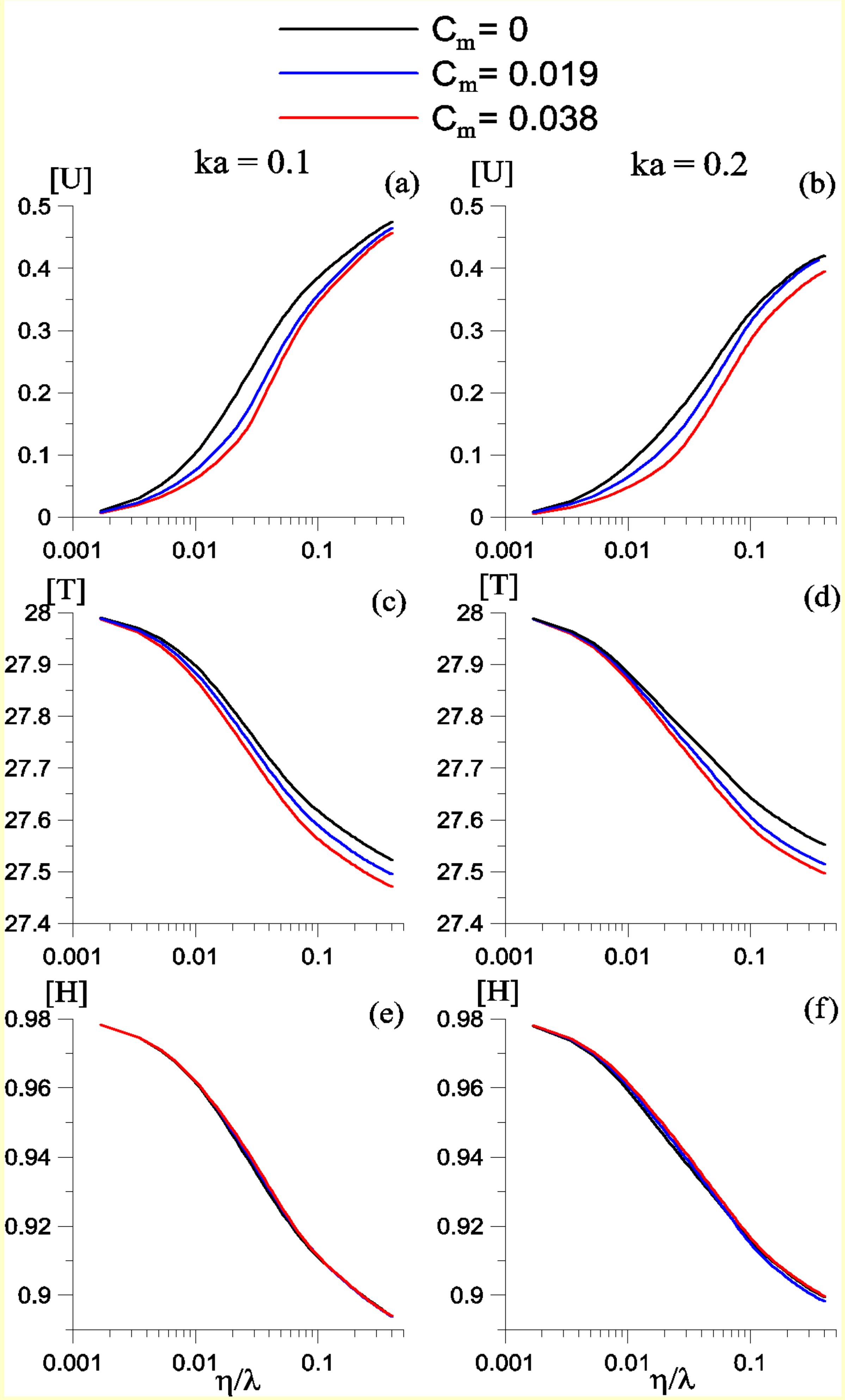


Mean flow profiles

Air Velocity

Temperature

Humidity



CONCLUSIONS

- Drops impose additional drag on the air and cool and moisten the air;

- the drops contribution to the enthalpy flux increases with diameter;

- smaller drops (d <150 μm) are mostly in the "wet bulb" state, i.e. do not provide enthalpy to the air;

- the dominant contribution in the enthalpy flux is that of latent heat of evaporation

Remaining problems:

-we need more accurate measurements of spray drops velocity distribution properties at injection in lab experiments;
- increase the bulk Reynolds number (better grid resolution);
- consider "polar low"s, i.e. really strong convection conditions