ON THE DYNAMICS OF A DRIFT FLOW UNDER LOW WIND

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OBJECTIVE

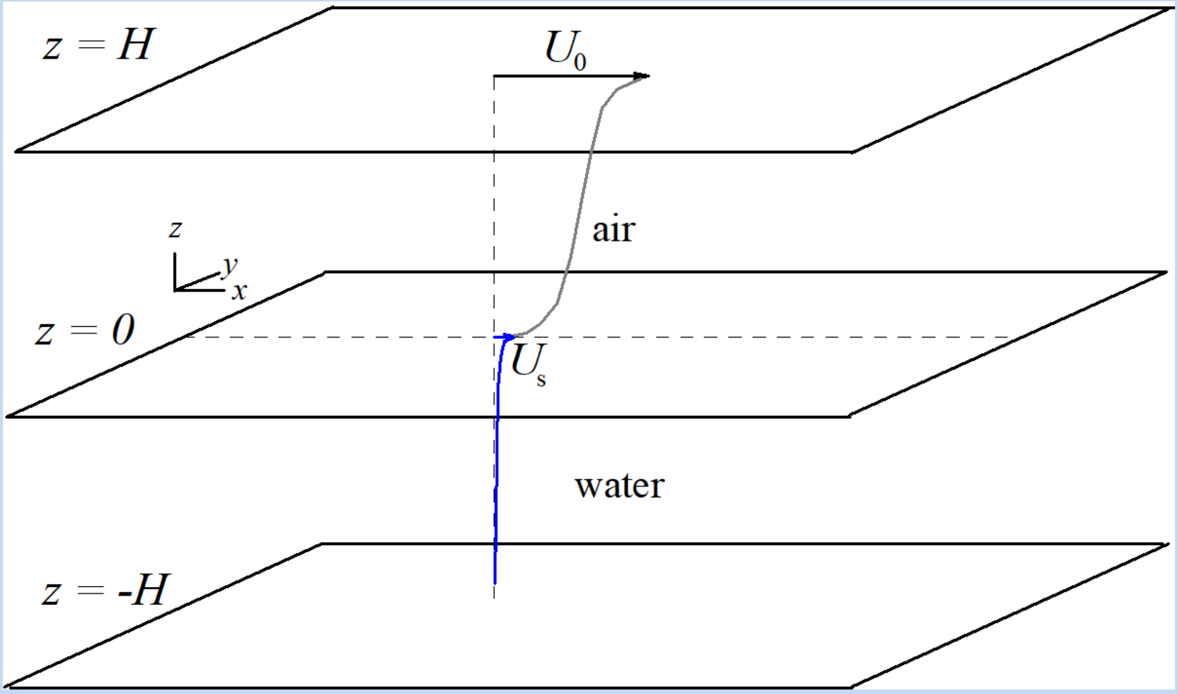
The studies (laboratory, numerical) of the wind-induced surface drift flow have been concerned mostly with moderate to strong winds (form 5 to 10 m/s) (*Banner & Peirson* 1998; *Cheung & Street R.L* 1988; *Longo et al.* 2012; *Polnikov et al.* 2020). This regime is characterized by the presence of surface (breaking and/or microbreaking) waves and underwater turbulence, contributing to the drift. The well-known parameterization of the surface drift under this "wave+turbulence" regime is (*Wu* 1975)

$$U_s \approx 0.53 u_*$$

A few studies (*Gemmrich & Hasse* 1992; *Shrira et al.* 2005) considered a sufficiently low-wind condition (below 2-3 m/s) where the water surface remains smooth. However, the question still stands how to parameterize the surface drift if the water flow remains quasi-laminar and the surface remains aerodynamically smooth.

This study addresses this problem by performing Direct Numerical Simulation (DNS)

Scheme of numerical experiment



Cartesian coordinates are considered, with coordinates x –along the mean wind direction (bulk velocity U_0, y – spanwise and z – vertical directions; $0 \leq x/H \leq 6$, $0 \leq y/H \leq 4$, $-1 \leq z/H \leq 1$ discretized on staggered, z-nonuniform grid of 360 × 240 × 360 nodes. DNS is performed simultaneously in two layers: $-H < z < 0$ – water, and $0 < z < H$ – air with an interface (water surface) at z = 0. Dirichlet (no-slip) conditions are put at the bottom (at rest, z = -H) and top (moving with U_0, z = H) boundary planes. All fields are periodical in x and y. At the water surface (z = 0) the continuity of momentum flux and mass conditions are imposed. The water surface is assumed to be flat throughout simulations.

Mathematical model

The Navier-Stokes equations are solved for air and water:

$$\frac{\partial U_i^{a,w}}{\partial t} + \frac{\partial}{\partial x_j}\left(U_i^{a,w} U_j^{a,w}\right) = -\frac{\partial P_{a,w}}{\partial x_i} + \frac{1}{\mathrm{Re}_{a,w}} \frac{\partial^2 U_i^{a,w}}{\partial x_j^2}, \qquad (1)$$

$$\frac{\partial U_j^{a,w}}{\partial x_j} = 0 . \qquad (2)$$

$U_i^{a,w}$ and $P_{a,w}$ - velocity and pressure in air (a) and water (w) ($i = x,y,z$),

$$\mathrm{Re}_{a,w} = \frac{U_0 H}{\nu_{a,w}} , \qquad (3)$$

is the Reynolds number, $\nu_{a,w}$ - kinematic viscosities, $8\cdot 10^3 < \mathrm{Re}_a < 2\cdot 10^4$,

$\mathrm{Re}_w = \mathrm{Re}_a \, \nu_a / \nu_w$.

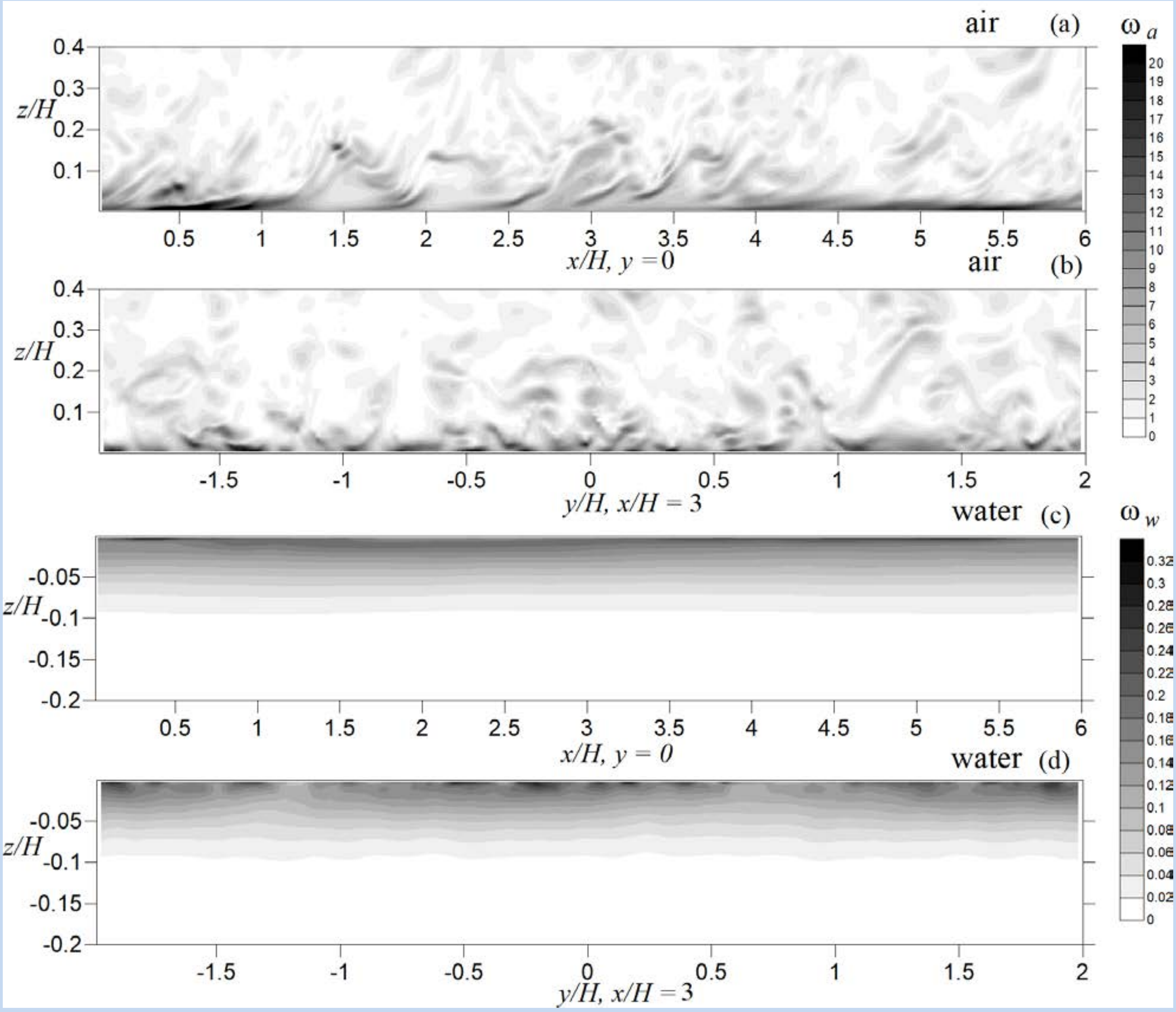
Boundary conditions at the water surface ($z = 0$):

$$\frac{\rho_a}{\rho_w} \frac{\partial U_{x,y}^a}{\partial z} = \frac{\mathrm{Re}_a}{\mathrm{Re}_w} \frac{\partial U_{x,y}^w}{\partial z} , \; U_{x,y}^a = U_{x,y}^w , \; U_z^a = U_z^w = 0 , \qquad (4)$$

where $\rho_a / \rho_w \approx 10^{-3}$ - the air/water density ratio.

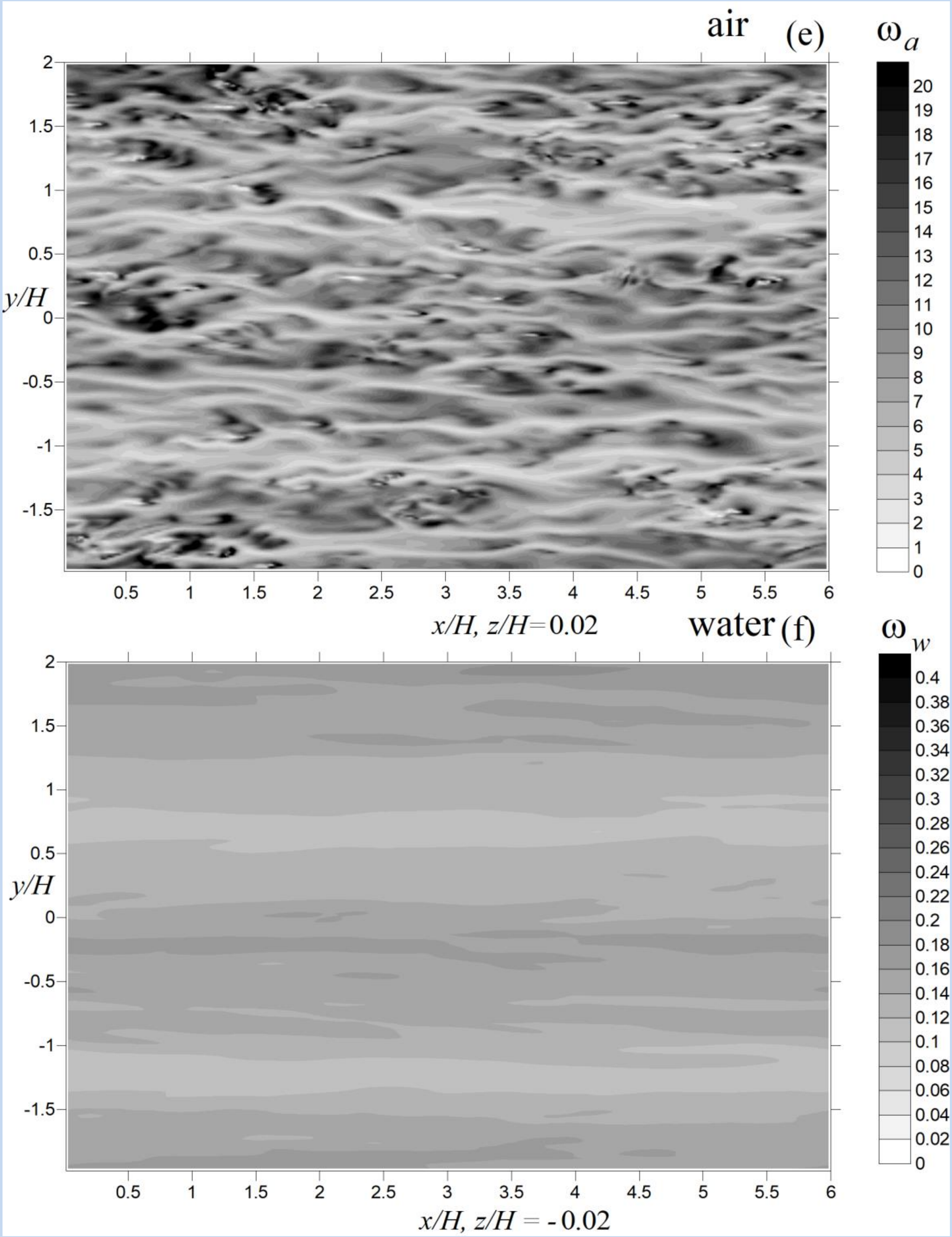
Initially the water is at rest, the air is slightly (~5%) perturbed.

Vorticity modulus $\omega_{a,w}$ in central planes (x,z) and (y,z) in air (a,b) and water (c,d) at $tU_0/H = 400$. $\mathrm{Re}_a = 1.5 \cdot 10^4$



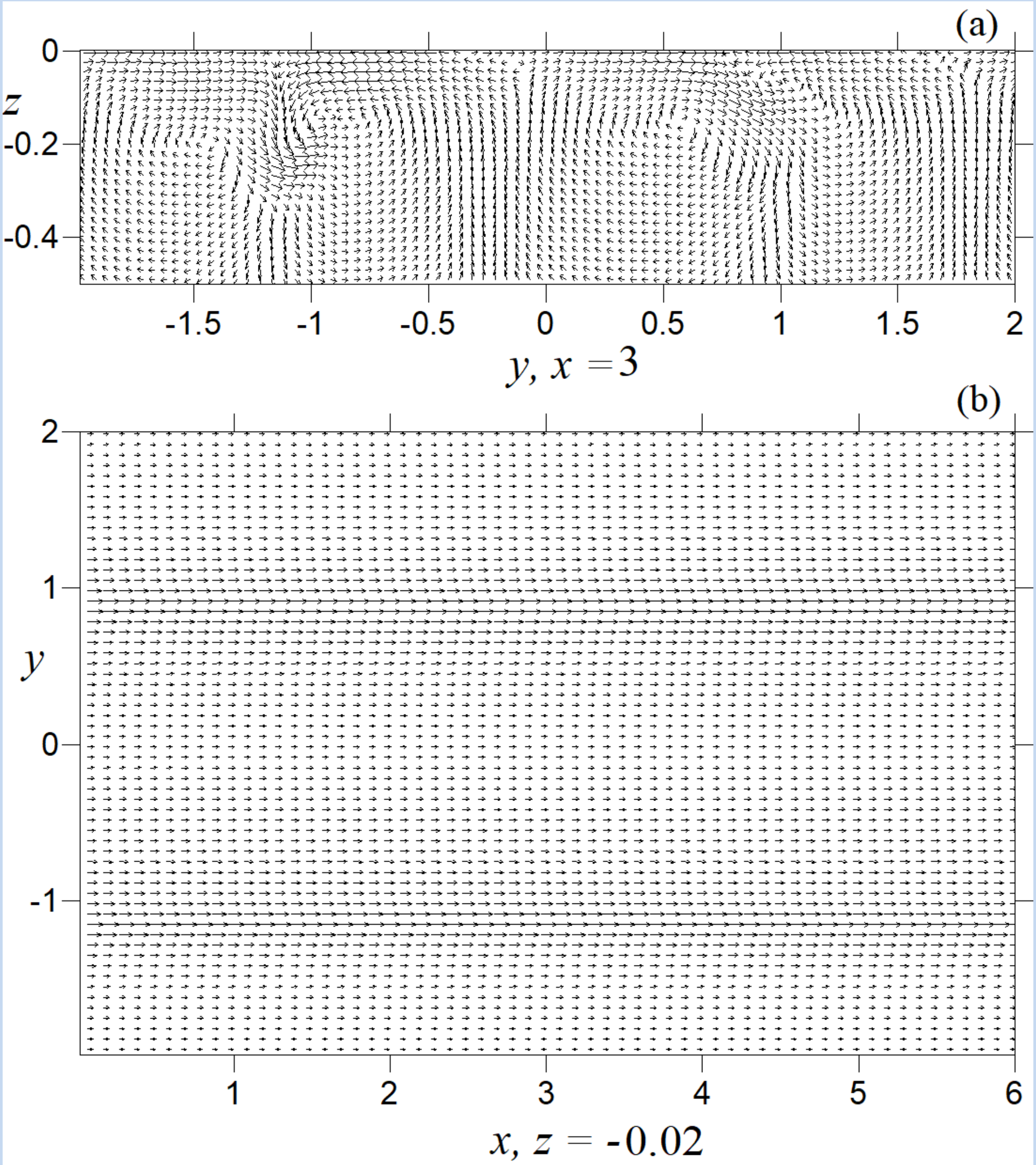
The air-flow is fully-developed and turbulent. The water-flow is quasi-laminar, $\omega_a \gg \omega_w$, and consists of streamwise-oriented streaks.

Vorticity modulus in horizontal (x,y) planes in air (e) and water (f) close to the water surface ($z/H = \pm 0.02$)

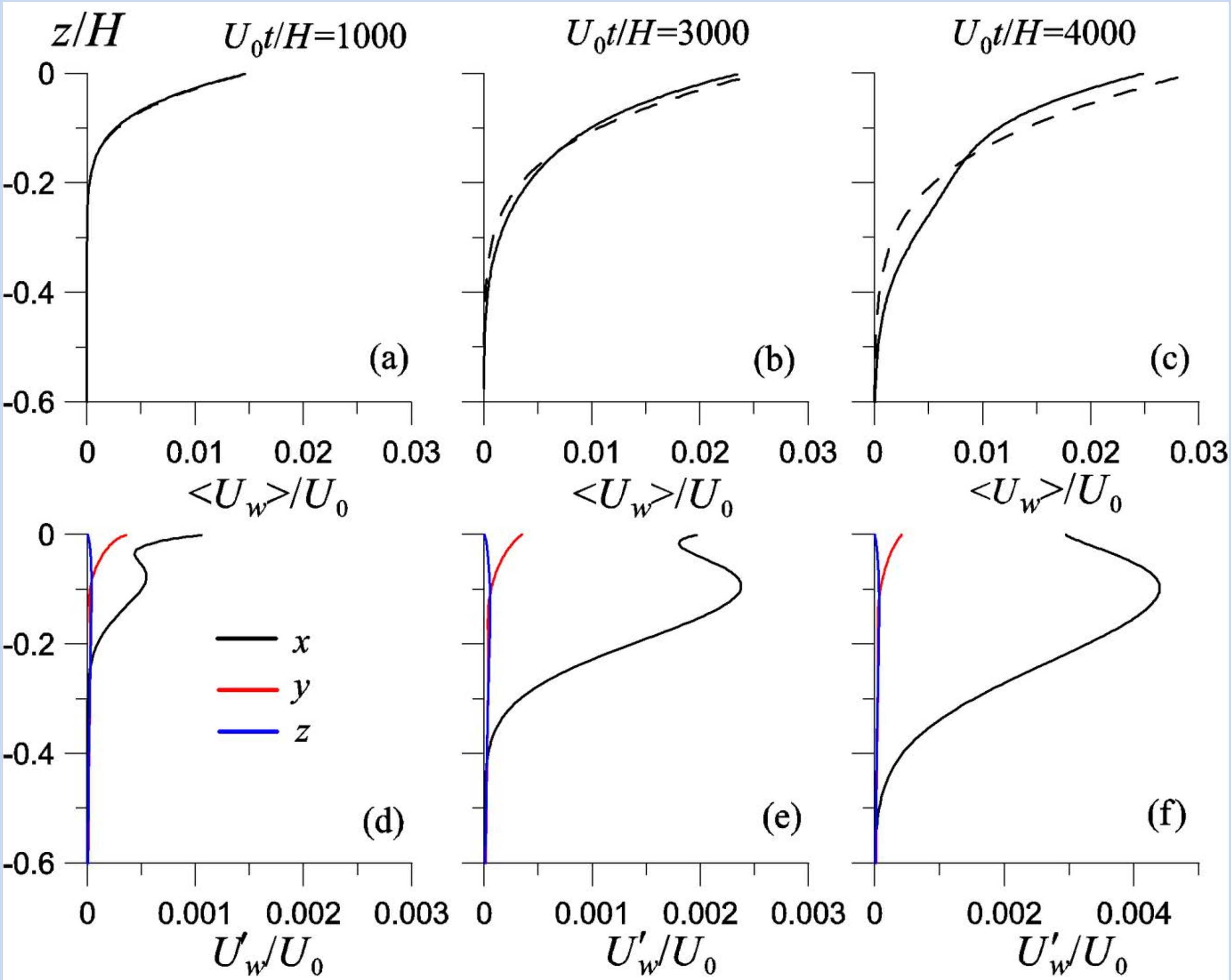


Velocity field in water in vertical (y,z) and horizontal (x,y) planes at времени

$tU_0/H = 4{\cdot}10^3$ ($\mathrm{Re}_a = 1.5{\cdot}10^4$)



Vertical profiles of mean drift flow (a,b,c) and fluctuations (d,e,f) at different times. $Re_a = 1.5 \cdot 10^4$



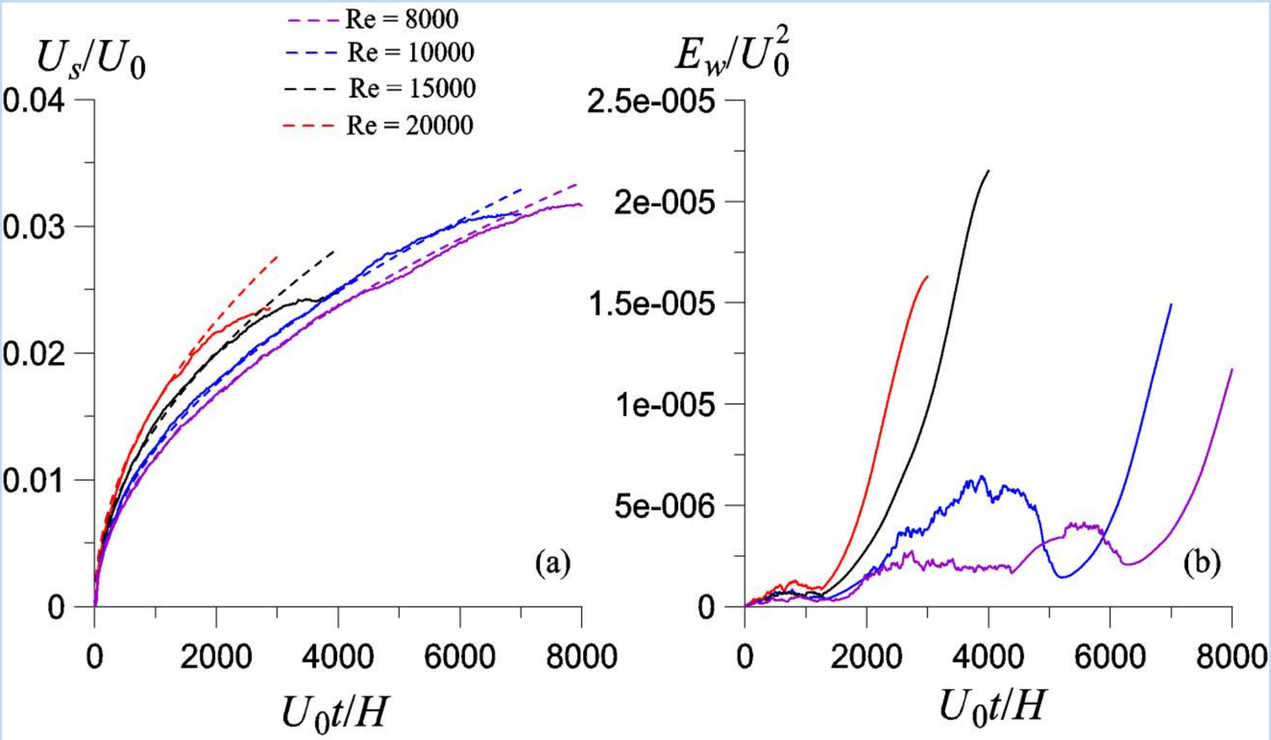
Dashed line is the analytical solution of the 1D Navier-Stokes ("diffusion") equation:

$$U_d^l(z,t) = -\frac{\partial U_d^l(0)}{\partial z}\left\{2\left(\frac{\nu_w t}{\pi}\right)^{1/2}\exp\left(-\frac{z^2}{4\nu_w t}\right) + z\,\mathrm{erfc}\left(-\frac{z}{2\sqrt{\nu_w t}}\right)\right\}, \qquad (5)$$

$$\mathrm{erfc}(z) = \frac{2}{\sqrt{\pi}}\int_z^\infty \exp(-x^2)\,dx$$

$$\frac{\partial U_d^l(0)}{\partial z} = \frac{\rho_a}{\rho_w}\frac{u_*^2}{\nu_w}, \text{ where } u_* \text{ is the friction velocity of air} \qquad (6)$$

Temporal development of surface drift velocity U_s (a) and kinetic energy of fluctuations in water E_w (b) for different Re_a

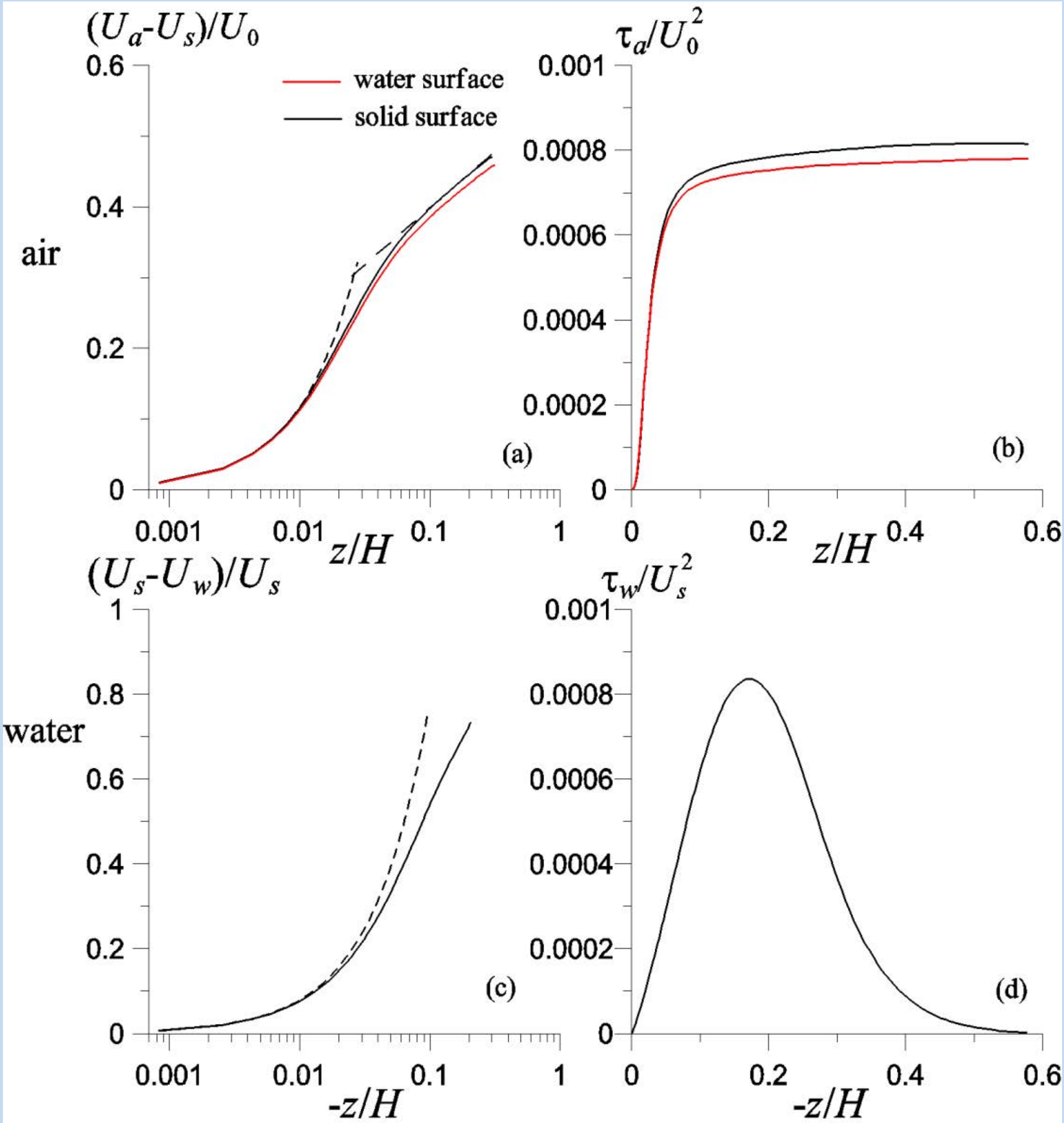


The dashed line is the analytical solution for U_s :

$$U_s = U_d^l(0,t) = 2u_*^2 \frac{\rho_a}{\rho_w}\left(\frac{t}{\pi \nu_w}\right)^{1/2} \tag{7}$$

The analytical solution agrees well with (7) when the fluctuations remain small, until their exponential growth.

Profiles of mean velocity $U_{a,w}$ and turbulent momentum flux $\tau_{a,w}$ of air (a,b) and water (c,d). $Re_a = 1.5 \cdot 10^4$



Dotted and dashed lines are for viscous and logarithmic asymptotics

Air: $$U_{visc} = \frac{u_*^2 z}{\nu_a}, \quad U_{\log}(z) = 2.5 u_* \left(\ln \frac{z u_*}{\nu_a} + 5 \right).$$

Water: $$U_s^{visc} = U_s + \left. \frac{\partial U_w}{\partial z} \right|_{z=0} z$$

Parameterization of surface drift under low wind

The Reynolds number of the drift flow:

$$\mathrm{Re}_d = \frac{U_s}{\nu_w}\left(\nu_w t\right)^{1/2} = \frac{2}{\sqrt{\pi}}\frac{u_*^2 t}{\nu_w}\frac{\rho_a}{\rho_w} \quad . \tag{1}$$

Turbulence in water develops at times $tU_0/H \approx 1.5\cdot10^3$ ($\mathrm{Re}_a = 2\cdot10^4$), $tU_0/H \approx 2.5\cdot10^3$ ($\mathrm{Re}_a = 1.5\cdot10^4$) , $tU_0/H \approx 4\cdot10^3$ ($\mathrm{Re}_a = 10^4$), $tU_0/H \approx 5\cdot10^3$ ($\mathrm{Re}_a = 8\cdot10^3$)], so for $\rho_a/\rho_w \approx 10^{-3}$ and $\nu_a/\nu_w \approx 15$ so that

the critical Reynolds number of the drift flow is defined from DNS:

$$\mathrm{Re}_d^c \approx 500 . \tag{2}$$

From (1) the time of transition to turbulence is

$$\frac{t_c}{\nu_w} \approx \frac{\sqrt{\pi}}{2}\frac{\mathrm{Re}_d^c}{u_*^2}\frac{\rho_w}{\rho_a} \ , \tag{3}$$

Then the critical surface drift velocity:

$$U_s^c = \left(\frac{2}{\sqrt{\pi}}\frac{\rho_a}{\rho_w}\mathrm{Re}_d^c\right)^{1/2} u_* , \tag{4}$$

Then for $\rho_a/\rho_w \approx 10^{-3}$ and $\mathrm{Re}_d^c = 500$ (4) gives:

$$U_s^c \approx 0.75 u_*$$

This is an upper estimate of the surface drift attained under low-wind at the stage where the velocity fluctuations are small and the surface remains aerodynamically smooth. For $U_0 \sim O(1\text{m/s})$ and $H \sim O(1\text{m})$ the transition time is of order $t_c \sim O(10^3\text{s})$.

CONCLUSIONS

The dynamics of a drift flow in the near-surface water layer driven by a turbulent air wind is investigated by direct numerical simulation (DNS). Comparatively low (up to $2 \cdot 10^4$) bulk Reynolds numbers of the air-flow are considered when the air boundary layer is turbulent but velocity fluctuations in the water are sufficiently small and the water surface remains aerodynamically smooth. It is shown that a drift flow develops in the near-surface water layer, and its velocity grows monotonically with time. At long times there develops an instability which leads to saturation of the growth of the drift-velocity. A threshold Reynolds number is defined in DNS under which the drift flow becomes unstable, and a parameterization of the surface drift velocity is formulated in terms of the air-flow friction velocity.

Publications:

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