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EFFECT OF SURFACE POLLUTIONS ON CONVECTIVE MIXING IN UPPER WATER LAYERS

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The influence of surface pollutions on the processes of convective mixing in the upper water layer is studied for different weather conditions. The authors' mathematical model of Langmuir circulations (LC) is employed. It is shown that pollutions reduce the intensity of LC motions and may even suppress them, especially at high wind velocities. They also increase both the surface current velocities and the velocity difference between the convergence and divergence areas in the LCs.

Convective mixing processes in the upper quasiuniform layer of a water basin play an important role in the formation of its thermal and hydrodynamic characteristics. Observations and theoretical studies indicate that the main cause of convection is the energy and mass exchange between air and water (explicit and latent heat flows, moisture flows). A significant portion of this exchange belongs to heat flows due to evaporation, which, under appropriate weather conditions, are the principal contributors to the cooling of the water surface [1]. Wind over the water basin restructures three-dimensional convective cells into spindle-shaped shafts extended along the wind direction, known as Langmuir circulations, which affect the entire quasiuniform layer. However, evaporation from the water surface strongly depends on its pollution.

According to the estimates reported in [2–5], evaporation may be reduced to 60%, which, in turn, affects the water surface temperature and the stability of water masses. Therefore it is of interest to find out how strongly and under what weather conditions surface pollutions (predominantly oil films) affect convective processes in a basin.

In this paper we examine this problem with the aid of our own mathematical model of Langmuir circulations [1, 6–11]. This model assumes that Langmuir circulations are axle-shaped vortical structures, extended along the wind direction and occupying the entire quasiuniform layer of the basin. Vortices are generated owing to convective instability of the water layer.

In this model, processes that occur in the basin are described by a complete nonlinear system of thermohydrodynamic equations in the Boussinesque approximation. The water surface is assumed to be free, and a wind of steady magnitude and direction is supposed to be blowing over it at velocity V. The interaction of water and air on the basin's free upper boundary is described by three semiempirical formulas:

$$\tau_0 = \rho_a C_U V^2 \tag{1}$$

for wind friction stress,

$$Q_T = c_p \rho_a C_T (T - T_a) V \tag{2}$$

for explicit heat flow,

$$M_q = C_q (q - q_a) V \tag{3}$$

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for moisture flux into the air due to evaporation, and

$$Q_q = LM_q \tag{4}$$

for latent heat flow that accompanies the moisture flux.

Here V is the wind velocity at some distance from the water surface; ρ_a is the air density; c_p is the air heat capacity at constant pressure; T and T_a are the water and air temperatures, respectively; q_a is the specific humidity of air at some height over the water surface; q is the specific humidity of saturated water vapor immediately at the water surface, determined by the surface temperature: $q = q(T)$; L is the specific heat of vaporization; C_U, C_T, and Q_q are the wind friction coefficient and the Stenton and Dalton numbers are for heat and water vapor transfer, respectively.

It follows from (1)–(4) that the interaction with the air is determined by the exchange coefficients C_U, C_T, and C_q. Observations and theoretical estimates indicate that it is the Dalton number C_q that depends most strongly on pollutions. Not going into the details of the dependence of C_q on the amount of pollution, we assume here that the actual value of the Dalton coefficient is $C_q = \eta C_{q\,\max}$, where $C_{q\,\max}$ is the Dalton coefficient for pure water. Thus, in this study we characterize the degree of pollution by the value of η and will analyze our model data as functions of η. This value varies from unity for pure water to zero for completely polluted surface.

Our model of convective mixing in a basin, which includes the Langmuir circulations generated, was described in detail in a number of our previous publications [1, 7–11] and will not be repeated here. We will only mention some basic points: the theory is based on the concept that all processes in water occur in a fully turbulized medium; the turbulence intensity (and hence also the micromixing, which determines the coefficients of turbulent viscosity and heat conduction in the medium) is calculated in the process of problem solution from the turbulent energy balance equation.

As was shown in the publications mentioned above, the strengthening of wind increases both the coefficient of turbulent exchange and the flows of latent and explicit heat. At high wind velocities ($V > 10$–16 m/s), the conditions of convection excitation are violated owing to the growth of the turbulent viscosity coefficient. At lower wind velocities (4–8 m/s) for pure water the flows of latent and explicit heat are sufficiently large to maintain convection. However, the presence of pollutions may significantly reduce latent heat fluxes, which leads to the suppression of convection and even, in some cases, to the "breakdown" of convective circulations. This greatly affects the velocities, the temperature distribution in the water, and the mixing, reducing the concentration of oxygen in the water and giving rise to other undesired consequences.

These arguments are illustrated by our data calculated using the proposed mathematical model.

Figure 1 shows one of the most important charactristics of the mixing process in a basin, the maximum vertical velocity in convective circulations $W_{\max}$, as a function of pollution (parameter η) for different values of the velocity of wind V over the basin. The figures on the curves denote the wind velocity values (in m/s).

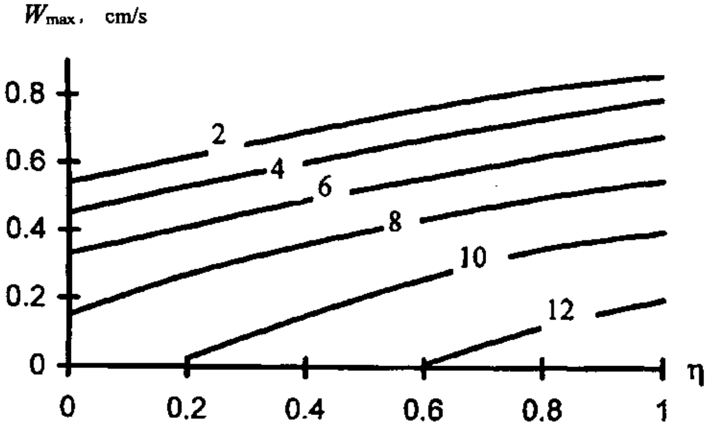

Fig. 1

The growth of the wind velocity over the water surface in the case of no pollutions ($\eta = 1$) decreases the motion intensity in Langmuir circulations. For instance, at the wind velocity $V = 2$ m/s the vertical velocity $W_{\max}$ in the convective structures is about four times higher than at $V = 12$ m/s. The presence of pollutions strongly affects the Langmuir circulation intensity, especially at high wind velocities. For $V = 12$ m/s and $\eta = 0.6$ (which corresponds to a 40% decrease of evaporation), Langmuir circulations cease to exist. For $V = 10$ m/s, the vortices disappear only at $\eta < 0.2$ (i.e., when evaporation drops by more than 80%). For slower wind velocities, Langmuir circulations exist even if no evaporation occurs at all ($\eta = 0$), owing to the explicit heat flow from water to air.

It is of interest to consider the current generated by Langmuir circulations on the basin surface. This current, directed along the wind, is different in different circulation regions. For instance, in convergence areas (Fig. 2) its velocity may be much higher than in divergence areas. The presence of pollutions considerably affects both the average water velocity on the basin surface and the velocity difference between the convergence and divergence areas ($\Delta U = U_{\text{con}} - U_{\text{div}}$).

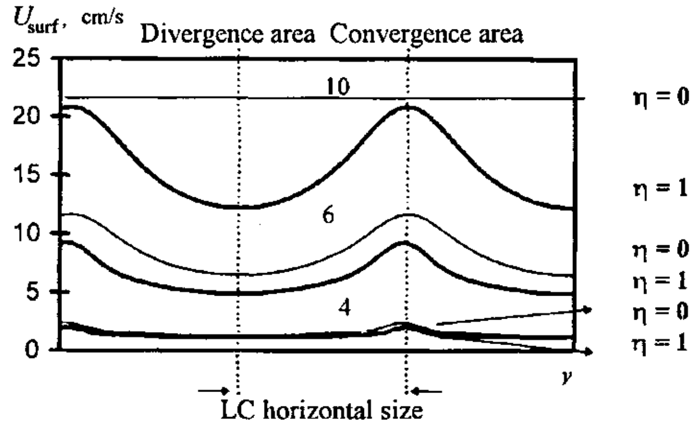

Fig. 2

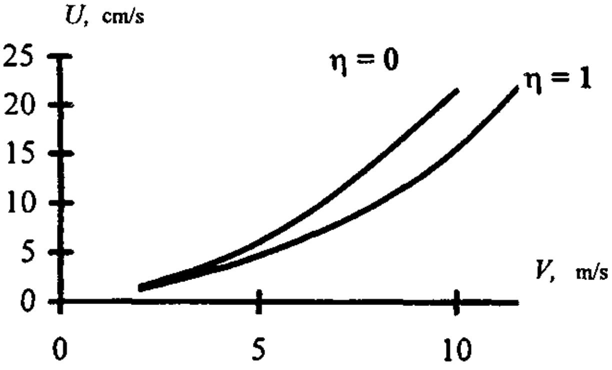

Fig. 3

Figure 3 shows the surface current average velocity U as a function of the wind velocity V for pure and polluted water surface (characterized by η).

At low wind velocities ($V \leq 4$ m/s) the surface velocity weakly depends on the value of η. At high wind velocities and with fully polluted water ($\eta = 0$), the surface current velocity becomes considerably greater than in the case $\eta = 1$ (no pollution). The difference for $V = 10$ m/s is about 6 cm/s (more than 30%).

Figure 2 gives an idea of how large are the velocity differences ΔU. It shows the distributions of the surface velocity U_{surf} in different areas of Langmuir circulations as a function of η for different wind velocities. The numbers at the curves denote the wind velocity (in m/s). The upper boundary of the region corresponds to $\eta = 0$ ($C_q = 0$), the lower, to $\eta = 1$ ($C_q = C_{q\,\max}$).

For wind velocity $V = 4$ m/s, water current velocities in Langmuir circulations on the surface weakly depend on η. With the growth of wind velocity, both the average velocity of drift and a velocity difference ΔU between different current zones increase. For instance, at $V = 6$ m/s the velocity difference ΔU is about 4 cm/s, and this value does not significantly vary with η. The picture becomes radically different at $V = 10$ m/s. Langmuir circulations exist for $\eta = 1$, and velocity difference ΔU is as high as 9 cm/s, while for $\eta = 0$ the circulations "break down" and the surface current becomes the same over the entire water surface.

Thus, our computer experiments indicate a strong dependence of Langmuir circulations intensity on the water surface pollution degree. This is primarily associated with the fact that pollution reduces evaporation from the water surface and hence decreases the energy flux needed to generate circulation structures. In some cases, this may lead to complete suppression of convection and mixing in the upper water layer.

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