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EFFECT OF WATER SURFACE POLLUTION BY PETROLEUM PRODUCTS ON THE FORMATION OF LANGMUIR CIRCULATIONS AND THE ENERGY EXCHANGE BETWEEN A BASIN AND THE ATMOSPHERE

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A novel mathematical model is used for investigating the effect of oil pollutions on the characteristics of Langmuir circulations and the streams of sensitive and latent heat from a basin into the atmosphere. Calculations have been performed for a wide range of wind velocities over the basin and for the values of Dalton's number which depends on the surface pollution. A range of parameters in which the Langmuir circulations disappear has been found. Estimates have been made of the temperature differences between the water surface and the air, as well as between the water surface and the bottom, as functions of wind velocity and Dalton's number.

The growth of petroleum production on the continental shelf and sea transportation of petroleum products leads to their increased inflow into the World Ocean. As a result, oil films appear on the water surface, which radically change the physical properties of the air–water contact zone. In particular, they change the water albedo, damp capillary and small-scale gravity waves, they change the water surface temperature, etc. The most strongly affected process is evaporation. According to available estimates [1–4], evaporation may decrease by as much as 60%. Thus, oil pollutions may exert global influence on the process of moisture penetration into the atmosphere, substantially change the flows of latent heat that cool the upper layer of basins, significantly affecting the climate in general.

The greatest effect on the processes of evaporation is produced by the water surface temperature. This temperature, in turn, is determined by the balance of the heat fluxes necessary for evaporation and the heat fluxes coming from the lower, strongly turbulized water layers. The processes, which determine the water surface temperature, depend substantially on the presence of oil films on the surface. In the present article we discuss a mathematical model of thermohydrodynamic processes in a basin, which allows one to evaluate the influence of an oil film on the processes of exchange between the basin and the atmosphere.

It is well known [5] that at wind velocities of up to 16 m/s and under different hydrometeorological conditions spindle structures may arise in upper water layers. These structures are referred to as the Langmuir circulations (LC). Their axes are directed along the wind current direction. The vertical dimensions of such vortices may amount to hundreds of meters, covering the entire quasiuniform layer and participating in its mixing. An analysis of the physical factors that determine the generation and existence of the LC shows that oil pollutions, changing the characteristics of the air–water contact zone may significantly affect the LC intensity and other parameters. The LC, in turn, shaping the thermal and dynamical structure of the ocean's upper layer, determine to a large extent, the income of heat and moisture from the ocean into the atmosphere.

The authors of some earlier studies [6, 7] have formulated a mathematical model of the Langmuir circulations, conducted a series of test calculations [8–11], and verified the model with the data of field observations [12]. In the present study the model is used for investigating the influence of oil films on the LC parameters, the flows of sensitive and latent heat from the water into the atmosphere under various weather conditions.

The basic theory of Langmuir circulations is described in detail in [6, 7]. The authors of these publications believe that the main cause for the generation of these circulations is unstable thermal stratification which occurs from radiative cooling of the basin, as well as from surface cooling due to the sensitive heat flux and evaporation. The drift current caused by winds shapes the convective structures into vortex circulations whose axes are oriented along the wind current direction.

An important statement of the theory is the fact that both the drift current and large-scale convective circulations exist in the conditions of well-developed turbulence (the typical Reynolds and Grashof numbers, Re and Gr, are 10^6 and 10^{12}, respectively). Such ordered vortical formations are regarded as coherent structures [13], and the technique described in [6] is employed for the construction of the model. This technique relies on the similarity, many times pointed out by various authors, between ordered motions under the conditions of well-developed turbulence (coherent structures) and secondary flows that arise in laminary flows upon the loss of stability under similar conditions.

The processes in a basin are described by the full nonlinear set of thermohydrodynamic equations in the Boussinesq approximation. We assume that the water surface is free and a wind of a constant direction and a constant velocity V blows over it. On the free upper surface of the basin, the water–air interaction is taken into account, and the momentum flux (the wind friction strain) τ_0 and the heat flux $Q_0 = Q_T + Q_q + Q_r$ are specified, where Q_r, the radiative heat flux, is assumed to be given, while the friction strain τ_0, the sensitive heat flux Q_T, and the heat consumption for evaporation Q_q are determined by the formulas

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

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

$$Q_q = L \rho_a C_q (q - q_a) V. \tag{3}$$

Here ρ_a is the air density, c_p is the air heat capacity at constant pressure, L is the specific heat of evaporation, C_U, C_T, and C_q are, respectively, the wind friction coefficient and the Stanton and the Dalton numbers for heat and water vapor transfer, T_a and q_a are the air temperature and the relative humidity; T and q are the water temperature and the relative humidity at the water surface.

In the present paper we investigated the influence of changes on the exchange characteristics, mainly the Dalton number C_q (see (3)), on the LC characteristics and on the fluxes of latent and sensitive heat from the water into the atmosphere.

We used the data of actual observations of LC in the Mozhaisk reservoir on May 22, 1979 [12], with the following hydrometeorological parameters: the depth of the upper mixed layer, $H = 3$ m; the air relative humidity, $f = 87\%$; the air temperature, $T_a = 6.5\,^\circ$C; the water temperature at the bottom boundary of the LC existence domain, $T_b = 12.77\,^\circ$C. The investigations were carried out in the wind velocity V range of 2 to 14 m/s for different values of the Dalton number C_q. It was assumed that the presence of an oil film can reduce the Dalton number. The nominal values of the exchange coefficients C_{Tn}, C_{qn}, and C_{un}, as in [12], were assumed to be equal to 1.5×10^{-3}, 1.5×10^{-3}, and 1.025×10^{-3}, respectively. In the calculations we used $C_q = C_{qn} \cdot \eta$, where η assumed the values 0, 0.2, 0.4, 0.6, 0.8, and 1.0.

The calculations yielded temperature distribution fields, current and velocity functions for ordered structures, temperature profiles and velocities for the drift (average) current, turbulent viscosity coefficients, and some other characteristics of Langmuir circulations.

The circulation intensity is most strongly dependent on the Dalton coefficient C_q. Figure 1 shows the maximum vertical velocity in the circulations ($W_{\max}$) in the water lowering zones as a function of the coefficient η at various wind velocities. The intensity of motion in the circulation structures is the highest at $\eta = 1$ and decreases with the Dalton coefficient decrease. At high wind velocities, a decrease of the Dalton coefficient may even lead to a breakdown of the circulation structure excitation.

Figure 2 shows the vertical profiles of the mean temperature in the circulation structures for different values of wind velocity and the Dalton coefficient. Increased pollution (i.e., decreased value of η) significantly

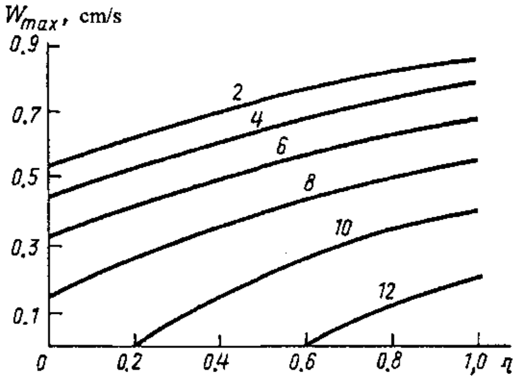

Fig. 1

Maximum vertical velocity $W_{\max}$ of fluid motion in circulations as a function of η. The numbers at the curves denote the wind velocity (m/s).

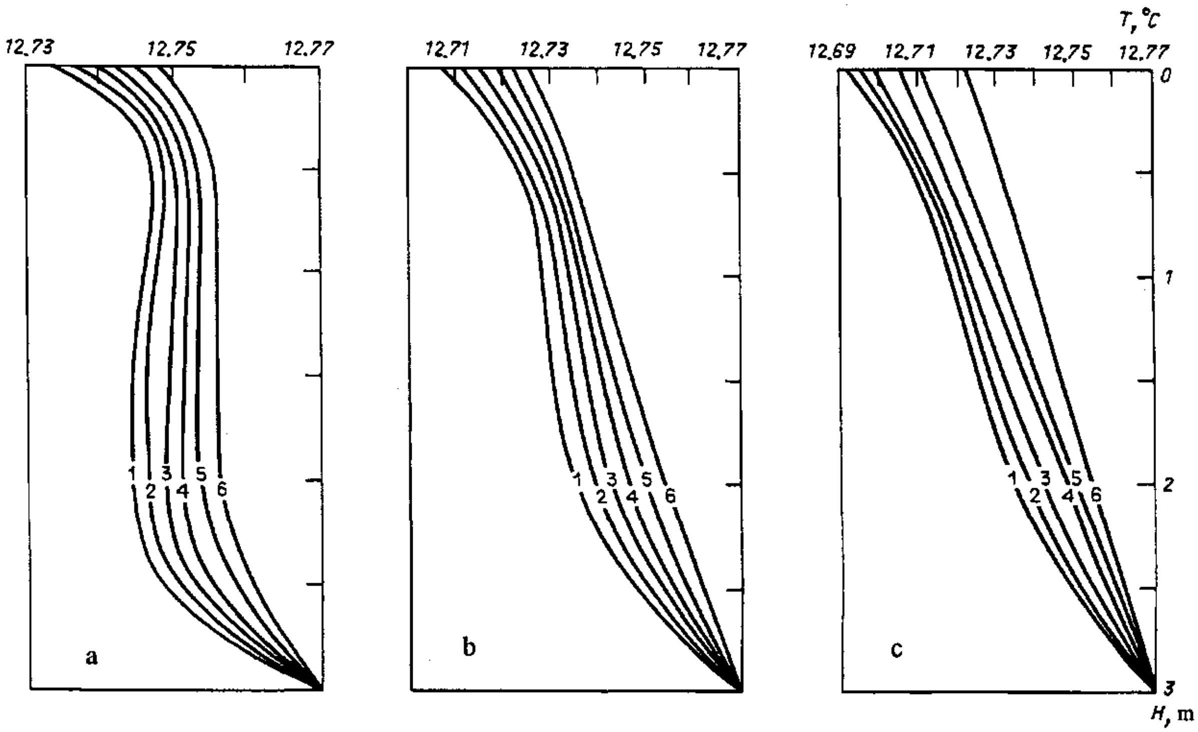

Fig. 2

Vertical profiles of mean temperature for wind velocities $V = 4$ (a), 8 (b), and 10 m/s (c), for $\eta = 1$ (*1*), 0.8 (*2*), 0.6 (*3*), 0.4 (*4*), 0.2 (*5*), and 0 (*6*).

affects the water temperature field. In particular, in the presence of Langmuir circulations all significant temperature changes are concentrated near the water surface and the lower boundary of the circulations, while a virtually isothermal layer is created in the central part of the vortex (the flow core). This is most clearly seen in Fig. 2*a*. With increasing wind velocity and decreasing η the vortices disappear, and the temperature profiles become practically linear (Fig. 2*b*). The reason for the formation of such a profile is discussed in detail in [8, 14]. As is seen from Fig. 3, when η, and hence also the Dalton coefficient C_q, decrease at the same wind velocity, the temperature difference $(T_b - T_s)$ between the basin's bottom and the surface decreases; if the wind velocity increases with the same value of η, the temperature difference grows.

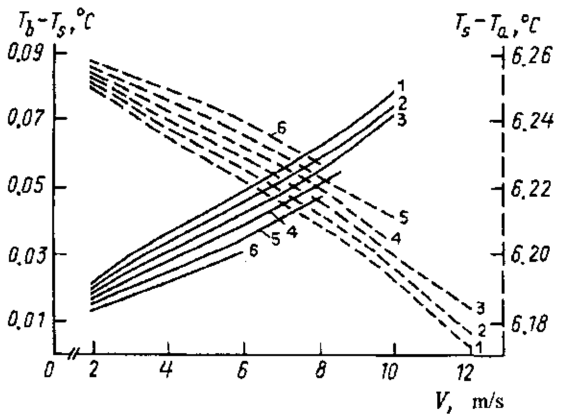

Fig. 3

Temperature difference $T_b - T_s$ between the basin bottom and the atmosphere (solid curves) and $T_s - T_a$ between the basin surface and the atmosphere (dashed curves) as functions of wind velocity V for $\eta = 1$ (*1*), 0.8 (*2*), 0.6 (*3*), 0.4 (*4*), 0.2 (*5*), and 0 (*6*).

In the first case the water masses become more stable, in the second one less stable. The temperature difference $(T_s - T_a)$ between the water surface and the air (Fig. 3) displays an opposite trend and does not exceed 1.5% of the smallest value of the drop for any values of the meteorological parameters.

The dependences of Fig. 1 can be used in practice for indirect evaluation of the effective (averaged over the water area) Dalton coefficient from the measured data on the Langmuir circulation parameters under different weather conditions.

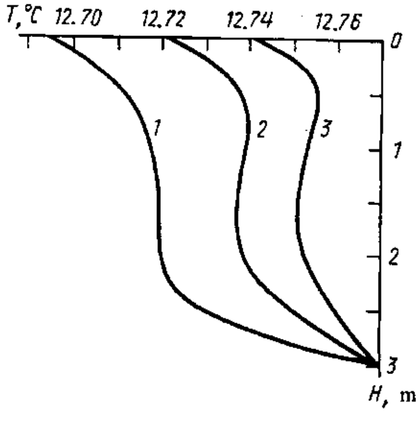

Fig. 4

Temperature profiles calculated by the model: in the convergence zone (*1*), at the vortex center (*2*), and in the divergence zone (*3*). The wind velocity is $V = 6$ m/s, $\eta = 1$.

It should be noted, however, that the measurement of the parameters that characterize the intensity of circulations and the comparison of these parameters with model calculation data are extremely complicated because the temperature field in a vortex has a substantial spatial variability comparable with the expected measurement data, while the measured values are very small (hundredths of a degree Celsius). This is well illustrated by Fig. 4 (taken from [12]) which shows the temperature profiles in different regions of a Langmuir circulation: in the convergence and divergence zones and in the middle part of the vortex. The values in different zones are significantly different. For instance, the temperature difference in the convergence and divergence zones at the water surface is about 0.04°C, which is of the same order with the difference in temperature between the upper and the lower boundary of the modeled region.

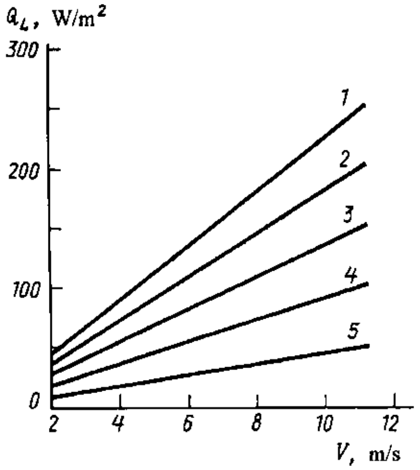

Fig. 5

Latent heat flux Q_L as a function of wind velocity V for $\eta = 1$ (*1*), 0.8 (*2*), 0.6 (*3*), 0.4 (*4*), and 0.2 (*5*).

The calculations performed allow one to evaluate the fluxes of latent and sensitive heat, as well as the amount of moisture transferred from the ocean into the atmosphere depending on the water surface pollution. This dependence is strong for latent heat flux as is seen from Fig. 5. In the wind velocity range under investigation, a twofold decrease of η decreases the latent heat flux from the basin into the atmosphere Q_q, and hence also the moisture income into the atmosphere due to evaporation by the factor of two. For significant wind velocities (8–12 m/s) the presence of pollutions may substantially change the energy balance of the air–water interaction. It must be noted, however, that small variations in the temperature difference between the water surface and the air affect insignificantly the fluxes of latent and sensitive heat.

Thus, our data demonstrate that the Langmuir circulations determining the temperature of the basin upper layer are quite sensitive to the parameters that describe the processes in the air–water contact zone, first of all to the Dalton coefficient. The latter, in turn, is to a large extent determined by the presence of pollutants, including oil films, on the water surface.

The proposed mathematical model makes it possible, on the one hand, to model various thermohydrodynamical situations in water basins, associated with water surface pollution, and, on the other hand, to evaluate with the aid of field measurement data the parameters (such as C_q) that account for the presence of pollutions, as well as their influence on large-scale processes of ocean-atmosphere interaction. Thus, the Langmuir circulations can be regarded as an important indicator of the state of water basins; in particular, measured data of their characteristics can be used for quantitative evaluation of pollution parameters and for ocean environment monitoring.

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