Numerical study of oil pollutant transport in a shore zone by means of eddy-resolved model

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A stream caused by intense cooling of a water surface is examined in a stratified water body with an inclined bottom. An arising buoyancy flow causes development of convective coherent structures in the form of vertical streams of cooled water. The influence of inclined topography generates the system of active convective eddies, which form closed circulation cells. In case of pollutant emission, these cells serve as stagnant zones, where the pollutant is detained. The evolution of buoyant oil fractions emitted into a water body due to leakage from an underwater oil pipeline is studied.

Oil-gas fields are sources of intense pollution of land waters in the Western Siberia. Lakes and inland water bodies having no mechanisms of the ecological relief such as, for example, natural watercourses, are the most vulnerable areas affected by the waste oil products. In this connection, it is quite urgent to study the mechanisms of redistribution of oil pollutants due to dynamic processes in a water body.

The overwhelming majority of lakes in the Western Siberia is shallow and has flat bottoms. Frequent and sharp temperature drops, leading to intense cooling of the surface layer, characterize weather conditions of the northern summer. At high winds, the leading heat exchange mechanism in epilimnion is the forced convection, and under the close-to-calm conditions, the vertical exchange develops due to the thermal conditions.

The phenomenon of free convection in shallow water bodies is very poorly studied. This is caused both by the difficulties in obtaining the field information and the absence of mathematical apparatus for a detailed description of small-scale hydrothermal processes. The numerical study of the penetrative turbulent convection in a water body was conducted in Ref. 1 based on a large eddy simulation (LES) method assuming the processes to be horizontally homogeneous (on the average). Meanwhile, the investigation of real water objects has shown[2] that topographic features of the bottom can be important factors of the formation of near-shore hydrothermal currents.

This paper presents the study of mechanisms of formation of the near-shore currents in a water body under intense cooling of its surface, when vertical mixing is determined, to a significant degree, by buoyancy forces. A numerical model with high spatial resolution of large-eddy turbulent structures is applied for description of the convective conditions. The resulting hydrodynamic fields are used for simulating the processes of redistribution of the emergency emissions of oil from an underwater pipeline.

Statement of the problem

The basic equations of the model are formulated in the Boussinesq approximation; they express the laws of conservation of momentum, heat, and mass of a turbulent fluid.[3] The non-hydrostatic form of the equations allows us to reconstruct the wide spectrum of motions in a water body, including direct description of the convective coherent structures. Subgrid-scale motions are parameterized using the LES method.[4] The results presented here have been obtained by use of the model from Ref. 3 improved by abandoning the periodic conditions at the side boundaries of a domain and considering the equations in terms of complete (non-split) hydrodynamic fields. This circumstance allows us to formulate physically meaningful problems, in particular, to simulate a current in a water body with an uneven bottom.

Omitting here the derivation of the equations of evolution of the hydrothermodynamic fields, consider only the boundary conditions accounting for the local character of phenomena under study. At the domain boundaries, the velocity vector $\mathbf{u} = (u, v, w)$ in the rectangular Cartesian coordinate system can be presented as $\mathbf{u} = \mathbf{u}_n + \mathbf{u}_s$, where $\mathbf{u}_n$ is the normal component of the velocity, and $\mathbf{u}_s$ is its tangent component. At the solid boundaries (shore line and bottom), the following conditions are formulated:

$$\mathbf{u}_n = 0;\ K\frac{\partial \mathbf{u}_s}{\partial \mathbf{n}} = C_D|\mathbf{u}_s|\mathbf{u}_s;\ T = T_s, \quad (1)$$

where K is the turbulent exchange coefficient; T_s is the preset temperature of the solid boundaries; C_D is the drag coefficient; s is the coordinate along the vector $\mathbf{u}_s$; $\mathbf{n}$ is the normal to the boundary.

The open side boundaries can be present in the case, when the computational domain covers only a

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part of the water body. Then, the conditions at the liquid boundaries are formulated as

$$\frac{\partial \mathbf{u}_n}{\partial n} = \frac{\partial \mathbf{u}_s}{\partial n} = 0, \ \frac{\partial T}{\partial n} = 0. \quad (2)$$

At the free surface ($z = 0$), the boundary conditions have the form

$$K\frac{\partial u}{\partial z} = \frac{\tau_x}{\rho}, \ K\frac{\partial v}{\partial z} = \frac{\tau_y}{\rho}, \ w = 0, \ K\frac{\partial T}{\partial z} = -\frac{B_0}{\rho c_p},$$

where τ_x and τ_y are the tangent stresses due to wind in the x-and y-directions; ρ is the water density; B_0 is the thermal balance of the water surface. The effects of interaction with the surface layer are insignificant in the problem under study, therefore τ_x, τ_y, and B_0 are believed known. The quiescent state is taken as the initial condition.

Numerical experiments

Consider a model water body with an inclined bottom bounded by the shoreline from the left ($x = 0$) (the geometry of the water body bed is shown in Fig. 2). The right boundary ($x = 100$ m) is believed open. The initial temperature distribution was constant at the surface (15°C) and decreased with depth by the exponential law with the gradient of 0.1°C /m, that is, it was characterized as stable. Specify the intensity of the surface heat outflow as $B_0 = 400$ W/m^2 characteristic of the conditions of strong cooling[5] and consider the problem without wind ($\tau_x = \tau_y = 0$). The numerical method for solution of this problem has been considered in Ref. 1; the calculations were made with the time step of 10 s on a 128 (horizontal) × 80 (vertical) grid with uniformly arranged nodes.

With the decrease of the surface temperature and development of convective instability, a system of thermics, transporting cold-water masses downward, is formed in the upper water layer. Areas with downward currents form narrow jets, between which the relatively low ascent of warm water from lower layers is observed. The characteristic horizontal dimension of the jets is about 3–4 m, and the amplitude of flow rates is small: the extreme values of w do not exceed 1 cm/s. The horizontal structure of the temperature field is practically constant, while the vertical structure is characterized by the sharp change near the surface due to the diffusion mechanism of heat exchange and the presence of the mixing layer, formed due to convective exchange, in the central part of the area. This is demonstrated by curves *2* and *3* in Fig. 1. These curves have been drawn in the $x = 33$ m cross section at the time of 40 and 60 min after the beginning of integration. The pattern described is characteristic of cooling convection in the upper mixed layer of a deep water body.[3,4]

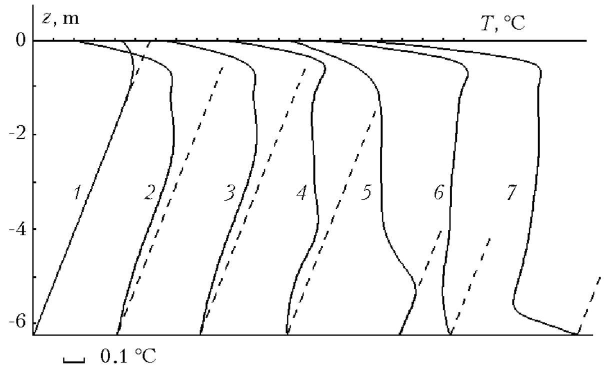

Fig. 1. Sequential stages of evolution of the vertical temperature profile in the cross section $x = 33$ m (curves *1*–*7*). The dashed line shows the initial distribution $T(z)$.

In the course of further cooling of the surface, the scales of the thermics increase and the flow rates inside the vertical jets increase too. The mixing layer propagates in depth and reaches the bottom layers (curves *4*–*6* in Fig. 1 show the evolution in a 30-min interval) first in shallow water and then in the entire water area. Dynamic coagulation processes develop, in which larger thermics take up neighboring smaller ones. By the time $t = 140$ min, two powerful convective jets with the downward flow rate of 4–6 cm/s are formed along with a number of small satellite thermics falling in the zone of influence of these jets. This period is illustrated in Fig. 2 by isolines of the field w (solid lines), where the letters A and B identify eddies with extreme amplitudes.

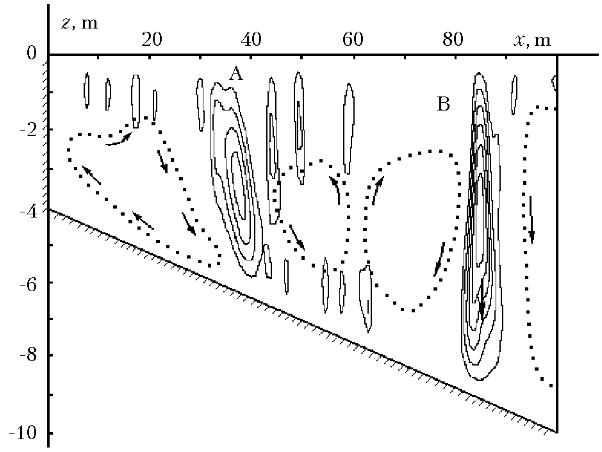

Fig. 2. Isolines of the vertical flow rate $w < 0$ drawn with the step of 1 cm/s (solid lines) and contours of closed circulations (dotted lines) at $t = 140$ min.

Vertical jets, involving the water layer to the bottom, play the role of cross barriers, that is, they become impenetrable for horizontal water currents. As a result, a closed circulation cell, shown by the round dotted line in Fig. 2, is formed between the shore and the A eddy. The same rotor, but with the opposing direction of rotation, is formed on the other side of the jet. The direction of motion in the upper part of the rotors is such that small thermics, produced in the surface layers, are entrained by the convergent flows to the top of the eddy A and taken up by it. This process is clearly seen in Fig. 2. The "attraction zone" of a large eddy is determined by the dimensions of circulation generated by it and, according to Fig. 2, is about 60 m along the x-axis. Similar processes develop in the zone of influence of the B eddy, as well.

The spatial position ($x_A \approx 37$ m) and configuration of the eddy A remain unchanged for a long time. However, with the release of the available potential energy and its transformation into the kinetic one, the energy scale of the near-shore circulation increases, which cases the tendency to expulsion of the A eddy toward the open boundary, where its motion forces the eddy B (see Fig. 2). The result is the development of an alternative mechanism of energy release through a barrier jet by means of generation of a cascade of convective structures in the near-bottom area. In Fig. 2, we can see five thermics, having separated from the lower part of the A eddy and moving downward along the slope in the direction of the B eddy. They can be interpreted as energy quanta, through which the excess energy from the A eddy is transferred to the eddy B, thus reloading the near-wall area. This interaction between the eddies provides for stability of the system, and its realization becomes possible under conditions allowing the development of daughter coherent structures in the near-bottom area. The positive buoyancy, created by the warm bottom relative to the sunken cold water, causes formation of another, deep convection layer. The characteristic temperature profile at double convection has two zones of hydrostatic instability with the negative gradient T_z, as shown by curve *7* in Fig. 1.

The described structure of the current is long-lived and has common features with the so-called "thermobar" effect in a deep lake.[2] Although this effect has a different physical nature and incommensurable scale, the "microthermobar" considered in this paper also blocks the direct mass and energy exchange between the shore and open parts of a lake. The external causes of its formation are the intense surface cooling and the presence of the shore and the inclined bottom. Thus, analogous experiment conducted for a water body with a flat (without a slope) bottom has shown that a powerful jet reaching the bottom is also formed near the shore, but does not fix in space and, moving toward the open boundary, leaves the computational domain with time. As a new near-shore eddy is generated, this process can repeat periodically. Thus, the bottom slope, causing the effect of energy penetrability of microthermobar, proves to be a significant factor of stability of the near-shore circulation.

Then, the evolution of the current is determined by the energy inflow to the system. As the surface heat flow weakens, the circulation can exist for a long time or decay. If the heat transfer through the surface continues with the initial rate, then the A eddy achieves the stage of energy saturation, when its power stops to increase, and begins to exert the frontal dynamic influence on the eddy B. By the time $t = 240$ min, the eddy B leaves the domain through the open boundary. The eddy A moves rapidly in the free space to the right boundary, and new eddy, consolidating small thermics, with roughly the same intensity arises at its place ($x = x_A$). As a result, the flow pattern at $t = 280$ min is qualitatively the same as shown in Fig. 2. From the viewpoint of energy analysis, the process of renewal of eddies is needed for short-time release of the boundary and transfer of accumulated kinetic energy through it. At constant B_0, the following changes of the eddy system have the cyclicity of 50–60 min.

Evolution of the pollutant field

Assume that an underwater pipeline springs a leak and oil products are emitted into the surrounding water area. The intensity of the emission is believed to be not very high, so that the presence of oil weakly affects the eddy dynamics. The density of the oil mixture is taken constant and equal to 0.9ρ, so that its ascent rate W_S is close to 1.2 cm/s (Ref. 6), which is comparable with the characteristic rates of convective pulsations. Consequently, the oil pollutant is considered as a passive admixture with positive buoyancy. Thus, the field of specific concentration of oil S can be calculated using the semiempirical equation of admixture transport and diffusion in the form[6]

$$\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} + v\frac{\partial S}{\partial y} + (w - W_S)\frac{\partial S}{\partial z} = \frac{\partial}{\partial x}K_S\frac{\partial S}{\partial x} + \frac{\partial}{\partial y}K_S\frac{\partial S}{\partial y} + \frac{\partial}{\partial z}K_S\frac{\partial S}{\partial z} + I_S, \qquad (3)$$

where K_S is the turbulent diffusion coefficient; I_S is the emission rate of the pollution source. The boundary conditions at all boundaries are set in the form

$$\frac{\partial S}{\partial n} = 0. \qquad (4)$$

The emission rate I_S is assumed constant in time and uniformly distributed over the pipeline length. The complex dynamic processes described above lead to formation of the "spotted" structure of the field S, varying widely in time. Restrict our consideration to the integral characteristic $\bar{S}(x,t)$, equal to the total amount of the admixture emerged to the surface for the time t. Figure 3 shows the spatial distribution of the parameter $\bar{S}/\bar{S}_{\max}$, where $\bar{S}_{\max}$ is the maximum possible layer of the admixture emersion, being close in value to the total emission volume.

Figure 3 is drawn for the 6-hour period, during which spatial inhomogeneities were evened.

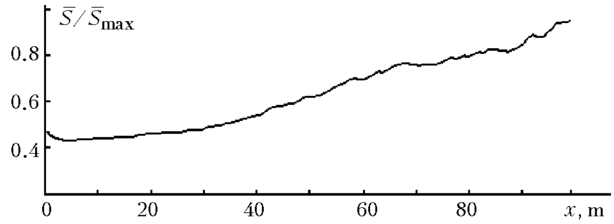

Fig. 3. Horizontal distribution of the normalized total amount of pollutant on the surface for 6-hour period.

The analysis of the figure shows that about 63% of the emitted oil is accumulated on the surface, while the rest part leaves the computational domain through the side boundary. The character of the irregularity is indicative of the dominant mechanism of horizontal redistribution of the pollutant from the shore to the open water.

Conclusions

The numerical model of a shallow water body with the possibility of reconstructing coherent structures of convective nature has been constructed. The numerical experiments have shown that the intense cooling of the water surface leads to formation of a spatially inhomogeneous fine structure of the current and a stable near-shore circulation with the characteristic properties of the thermobar. The mechanism of current self-sustaining due to energy exchange by means of large eddies has been described. It has been shown that macrocirculation can be broken for a short time with the release of the kinetic energy into the open part of a water body and then reconstructed.

Acknowledgments

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