Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 9 (2004), 43–49

Numerical modeling of convective currents in a reservoir coastal zone*

V.A. Shlychkov

Abstract. Peculiarities of the coastal flows in a water reservoir are mainly conditioned by a bottom geometry and coastal curvatures. The periods of conducting water layer cooling initiate an intensive vertical exchange which in turn generates a complex structure near the coastal flow. Such a mechanism of generation of flows is connected with evolution of the convective instability in a reservoir and significantly differs from the known mechanisms of wind and wind wave flows. The numerical modeling of the convective mode involves a necessity of direct reproduction of coherent structures stochastic ensemble. For this purpose an eddy resolving model of the upper mixed water layer with allowance for bottom roughness is used. The model results are used in solving the problem of the oil admixture transport in conditions of intensive surface cooling.

The coastal currents in a stratified reservoir are caused by complex mechanisms of heat and mass transfer influenced by the turbulent exchange, superficial interaction with atmosphere, wind stress, free convection, bottom topography forcing, coastal line indentation, etc. While a forced convection is the main mechanism of the heat exchange in epilimnion in conditions of strong winds, in conditions close to calm conditions, thermal convection causes a vertical exchange.

A free convection phenomenon in shallow reservoirs is partially investigated. This is caused by both the problems of field data gathering and the absence of a mathematical tool for a detailed elaboration of small-scale hydrothermal processes. Work [1] presents a numerical study of the penetrating turbulent convection in a reservoir by the method of large eddies, assuming a homogeneity of horizontal plane processes (as a mean). Meanwhile, the real water body study has shown [2] that a specific bottom topography can appear to be an important factor of the coastal hydrothermal currents formation.

The object of the present study is mechanisms of the reservoir coastal currents formation with the intensive surface cooling when the vertical mixing is determined mainly by buoyancy. These processes are studied by the method of eddy simulation [3]. The eddy simulation models can obviously reproduce an energy-active part of a turbulent spectrum in contrast to a generally accepted way of modeling [2], where the whole turbulence is considered as an under-grid one, and only regular fluid motions are numerically

---

*Supported by the Russian Foundation for Basic Research under Grant 03-05-96825.

resolved. The eddy simulation approach turned to be rather fruitful in studying the boundary layer structure in conditions of convective instability when conventional models of turbulent closure inadequately reproduce the counter-gradient substance flows.

The turbulent coherent structures within the upper mixed layer of a reservoir with unstable stratification are realized as convective jets and thermics. These vertical structures do not change for some time, while jointly they form a convective ensemble with stochastic properties, since their spatial distribution is irregular [4]. To describe coherent structures, a numerical model with a high spatial resolution and detailed elaboration of large convective eddies is applied. This model was based on the integration of non-hydrostatic equations of hydro-thermodynamics in the Boussinesque approximation.

Let us set a Cartesian system of coordinates x, y, z, where the axis z is directed upwards, the axis x is a normal to the coast line. Now, within thermodynamic fields, let us single out the main current which reflects the initial temperature stratification of the reservoir

$$T = \overline{T}(z) + T', \quad P = \overline{P}(z) + p, \tag{1}$$

where $\overline{T}$, $\overline{P}$, $\overline{\rho}$ are, respectively, the assigned water temperature, pressure, and density, satisfying the equations of state and statics. The initial equations have the form

$$\begin{aligned}
&\frac{du}{dt} = -\frac{1}{\overline{\rho}}\frac{\partial p}{\partial x} + lv - \frac{1}{\overline{\rho}}\left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right),\\
&\frac{dv}{dt} = -\frac{1}{\overline{\rho}}\frac{\partial p}{\partial y} - lu - \frac{1}{\overline{\rho}}\left(\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right),\\
&\frac{dw}{dt} = -\frac{1}{\overline{\rho}}\frac{\partial p}{\partial z} + \beta_T T - \frac{1}{\overline{\rho}}\left(\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right),\\
&\frac{dT}{dt} + Sw = \frac{1}{\overline{\rho}}\left(\frac{\partial \sigma_x}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \sigma_z}{\partial z}\right),\\
&\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0,
\end{aligned} \tag{2}$$

where (u, v, w) is the velocity vector, T is temperature perturbations (the prime is omitted), l is the Coriolis parameter, β_T is a factor of thermal expansion of water, $S = \frac{dT}{dz}$ is temperature stratification, τ_{ij} are components of the turbulent strains tensor,

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}.$$

Consider the edge conditions with allowance for local nature of the phenomena under study. Set up a correspondence between the velocity vector $\vec{u}$ in the Cartesian rectangular coordinate system and the expansion $\vec{u} = \vec{u}_n + \vec{u}_s$ at the domain boundaries, where $\vec{u}_n$ is normal, and $\vec{u}_s$ is a tangential velocity component. For solid boundaries (the coast line and bottom), let us assign the following conditions

$$\vec{u}_n = 0, \quad K\frac{\partial \vec{u}_s}{\partial n} = C_d \left|\vec{u}_s\right| \vec{u}_s, \quad T = T_s, \tag{3}$$

where K is a turbulent exchange coefficient, T_s is the assigned temperature of solid boundaries, C_d is a resistance coefficient, s is a midcourse coordinate along the vector $\vec{u}_s$. The open lateral boundaries can be present in the case, when the calculation domain does not cover the whole reservoir but only its part. Conditions on liquid boundaries are then set as

$$\frac{\partial \vec{u}_n}{\partial n} = \frac{\partial \vec{u}_n}{\partial n} = 0, \quad \frac{\partial T}{\partial n} = 0. \tag{4}$$

The boundary conditions at the free surface $z = 0$ are the following:

$$K\frac{\partial u}{\partial z} = -\frac{\tau_x}{\bar{\rho}}, \quad K\frac{\partial v}{\partial z} = -\frac{\tau_y}{\bar{\rho}}, \quad w = 0, \quad K\frac{\partial T}{\partial z} = -\frac{B_0}{\bar{\rho} c_w}, \tag{5}$$

where τ_x and τ_y are wind stress tangents in x- and y-directions, B_0 is a thermal balance of the reservoir surface, c_w is a specific thermal capacity of water. The effects of interaction with the air layer over the water surface are parametrically described, therefore τ_x, τ_y, B_0 were considered as known values. The rest with a reservoir stable stratification over depth was accepted as initial conditions.

Parametrization of undergrid-scale motions and calculation of the turbulence fields τ_{ij}, K are carried out using the LES-method [5]. The results given below are obtained on the basis of the improved model [1, 6] due to rejecting the periodic conditions at the lateral boundaries of the domain and consideration of equations in terms of full (not split) hydrodynamic fields. This circumstance allows the formulation of problems with expressed physical properties, in particular, the modeling of a current in a reservoir with a rough bottom. The turbulent fluid current in the reservoir coastal zone is examined at a sharp temperature decrease in the surface air layer.

Let us consider a simulated reservoir with the inclined bottom, limited from the left ($x = 0$) by the coastal line (the bed geometry is shown in Figure 1). The water depth varies from 4 m near to the coast up to 10 m at the right boundary ($x = 100$ m), which is considered as open. The initial temperature distribution is assigned as steady and equal to 15°C at the surface and decreasing with depth from the linear law with a gradient of 0.1°C/m.

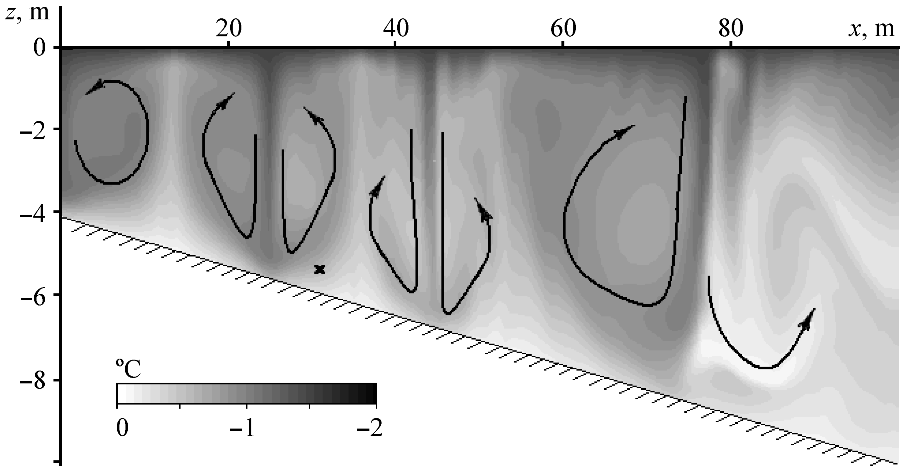

Figure 1. The temperature perturbation field in a calm reservoir at the time moment $t = 120$ min. The arrows show the direction of motions, the cross marks an emission site

Intensity of the surface heat outflow has the value $B_0 = 400$ W/m^2, typical of the night cooling conditions. The numerical method of solving the problem is stated in [1], the calculations were carried out on the grid with 128 points horizontal resolution, while the vertical resolution was 100 points between regular intervals, the time step being equal to 10 s.

Within this statement, three numerical experiments were carried out as follows: 1) calm conditions; 2) a wind from the coast to the reservoir – this situation is typical of the day time breeze; 3) a wind directed from water to the coast (the night time breeze).

As the surface temperature decreases and convective instability develops in the upper layer of the reservoir, the system of thermics is formed which transport cold water masses downwards. The areas with descending currents are localized into narrow jets. The typical horizontal size of jets at the initial stage is 3–4 m, the velocity range being insignificant – the extreme values of w do not exceed 1 cm/s. The process dynamics is typical of the formation of a mixed layer with penetrating turbulent convection [1], when the vertical heat exchange is realized as stochastic ensemble of thermics as coherent structures.

During further cooling of the surface, the sizes of thermics increase, and the velocities inside vertical jets grow. The mixed layer disseminates into depth and reaches bottom horizons. Dynamic processes of coagulation occur when more powerful thermics absorb closely located small structures. In time, a number of single jets and a set of short-lasting small thermics are formed in the area. Large jets generate superficial convergence affecting the small-scale structures. Carried away by convergent streams, thermics coalesce into the jet contributing to its intensity. The cooled water masses move downwards with a significant velocity (up to 10–15 cm/s) and, being reflected from the bottom, create a divergent current. Convection loses penetration properties, while the reflected currents work against buoyancy forces, filling up the accessible potential energy at the cost of the kinetic energy. Thus, the presence of bottom causes weakening of the convection energy efficiency.

The above-mentioned is illustrated by Figure 1, which shows distribution of temperature perturbations in a vertical plane at time $t = 120$ min, calculated without wind taken into account ($\tau_x = \tau_y = 0$). Areas with low temperature are marked with a darker fill of isotherms (Centigrade scale is given in the bottom of the figure). The arrows show a typical position of current lines close to eddies.

Analysis of Figure 1 shows that the developed convective exchange is realized by means of powerful vertical jets covering the whole water layer thickness. A typical horizontal size of the jet core with extreme values of w (areas of the expressed descending currents can be identified by dark vertical strips) does not exceed several meters, and the generated circulation cell has the size of 10–20 m. There are four such cells in Figure 1, and the coastal eddy (the left) is stationary and forms a motionless rotor with closed circulation. Eddies located to the extreme right, evolve changing their position and intensity as a result of coagulation and interactions with small thermics. Development of thermics can be seen, for example, in the cross-section $x \approx 80$ m, where a small eddy stands out, being transported by a convergent current and coming to the main jet from the right. Other small structures are located in the upper part of the area close to large eddies (see Figure 1).

If an impurity source is placed in any part of a reservoir, then the trajectories of particles will be defined by a complex current structure, when the configuration of the concentration field essentially depends on the source location and on the process stage. To calculate the field of oil concentration s, a semi-empirical equation of impurity transport and diffusion was used [7]. The present calculation simulates a distribution of substance emission with positive buoyancy from the submerged pipeline located in the coastal zone (the source coordinates are marked with a cross at $x = 33$ m in Figure 1). Since the oil distribution over the reservoir surface is of ecological importance, the time course of the horizontally averaged surface velocity u_0 and the volume of the emerged pollutant are analyzed. The diagram of u_0 as function of time is shown in Figure 2.

We see (Curve 1), that in calm conditions (i.e., without wind forcing), a stochastic convective ensemble generates a mean velocity which periodically changes its direction, transporting an impurity both to the coast and to the open part of the water area. The emerged impurity mass $\overline{s}_0$ normalized by

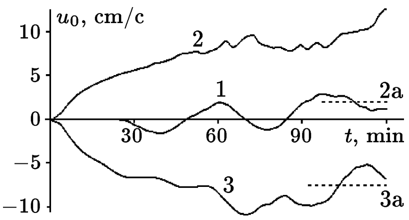

Figure 2. Time change of the horizontally averaged surface velocity in experiments 1, 2, 3 (curves 1, 2, 3 respectively). Dashed lines – a task without convection

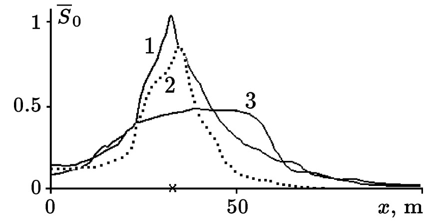

Figure 3. Spatial distribution of the normalized impurity mass at the surface in 2 hours in experiments 1, 2, 3 (curves 1, 2, 3 respectively). Source location at the axis is marked by cross

the maximal value, is shown in Figure 3 as Curve 1. The extreme surface concentration after two hours of the process development can be observed in immediate proximity from the site of deep emission ($x \approx 33$ m).

In the second experiment, the wind of 6 m/s strength, blowing from a water mirror line, is assigned. An arising drift current facilitates the outflow of coherent structures from the area that results in retardation of the convective exchange. The surface drift velocity reaching 10–12 cm/s (Curve 2 in Figure 2), is formed under the influence of the two factors: the wind stress and the surface convergence of convective origin, where convection is the dominant mechanism. It is seen from comparison of Curve 2 and the dotted line 2a (Figure 2). The dotted line characterizes velocity of a pure drift current without convective exchange ($B_0 = 0$ in conditions of (5)). We should note a significant increase (approximately three times as large) of the surface velocity as a result of interaction between the wind current and convection. Spatial impurity distribution over the surfaces does not undergo the qualitative changes (Curve 2 in Figure 2), however the total amount of the emerged pollutant turned to be 15% less than in the previous experiment, and the peak of concentration has slightly moved along the current, remaining close to the emission site.

In the third experiment, where the wind is blowing to the coast, the surface current direction varies to the opposite, as Curve 3 in Figure 2 shows. As in the previous case, the current precludes the fast development of convection. Only in the coastal zones, the character of middle circulation (counter-clockwise) stimulates the formation of a large positioned jet of the advective–convective nature similar to the structure with that presented in Figure 1. In time, a number of other eddies occur in the area, however owing to a different direction of transport in the upper and the bottom layers eddies are not fixed in space, but evolve and dissipate at random points of the area.

In the near-bottom layers, where an impurity source is located, the drift circulation causes mass advection to the open boundary (to the right). Under the influence of advection, the impurity particles get to dynamically developing convective currents and are quickly carried away from the emission site. As a result, the concentration field loses its pronounced character near the source and is as though "smeared" over space. The resulted distribution s_0 in the given experiment is shown by Curve 3 in Figure 3. The appreciable recession of the curve at $x \approx 60$ m forms a kind of the front moving to the open part of the water area and reflecting the internal dynamics of the convection process.

In conditions of a non-convective current ($B_0 = 0$), when the impurity redistribution is determined only by a drift stream and diffusion, the field s_0 has a pronounced pinnacled structure with a small width (10–15 m), where the value being extreme near the emission rapidly decreases with distance. Hence, it follows that the effects of cooling considerably affect the character of redistribution of the emerging oil pollutant.

The presented eddy simulation model of the thermal turbulent convection allows one to solve the problems of impurity migration in a reservoir of any shape. The solution of the related problems of ecological monitoring is also possible – for example, according to field data to predict the amount of deep emission and to identify a probable place of failure.

References

[1] Shlychkov V.A. Research of the vertical transport of buoyant impurity in a reservoir with the help eddy simulation model // Optics of the Atmosphere and the Ocean. — 2001. — Vol. 14, No. 6–7. — P. 633–636.

[2] Bocharov O.B., Vasil'ev O.F., Kvon V.I., Ovchinnikova T.E. Mathematical modeling of thermobar in a deep lake // Reports of the Russian Academy of Science. — 1996. — Vol. 349, No. 4. — P. 530–532.

[3] Large W.G., Gent P.R. Validation of vertical mixing in an equatorial ocean model using large eddy simulations and observations // J. Phys. Oceanogr. — 1999. — Vol. 29, No. 3. — P. 449–464.

[4] Monin A.S. On definition of coherent structures // Reports of the USSR Academy of Sciences. — 1991. — Vol. 318, No. 4. — P. 853–856.

[5] Moeng C.-H. A large-eddy-simulation model for the study of planetary boundary layer turbulence // J. Atmos. Sci. — 1984. — Vol. 41, No. 13. — P. 2052–2062.

[6] Shlychkov V.A. Numerical research of oil pollutants transport in a reservoir coastal zone with the help of eddy simulation model // Optics of the Atmosphere and the Ocean. — 2004. — Vol. 17, No. 7. — P. 571–574.

[7] Ozmidov R.V. Diffusion of Impurity in the Ocean. — Leningrad: Hydrometeoizdat, 1986.