Moscow University
Physics Bulletin
Vol. 52, No. 3, pp. 67–70, 1997

Vestnik Moskovskogo
Universiteta. Fizika
UDC 551.465

GEOPHYSICS

EFFECT OF WATER MASS AERATION ON VERTICAL TEMPERATURE DISTRIBUTION IN THE NEAR-THE-WATER LAYER OF THE ATMOSPHERE

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Experimental data on the vertical temperature distribution in a thin near-the-water air layer over aerated and nonaerated water have been reported. The heat flux from aerated water into the atmosphere, other conditions being equal, is higher than that from nonaerated water.

In the problem of heat and mass exchange between the atmosphere and the hydrosphere under the conditions of free convection, the effect of the degree of aeration of water masses on heat and mass losses of water basins remains poorly known. However, aeration is inherent in virtually all natural basins and results both from natural causes (the processes of photosynthesis, wind wave collapse, bottom gas sources) and from processes associated with human activities. Water aeration is the highest in the coastal zones of seas and oceans, where shallow depths make waves steeper, leading to their intense collapse, and where strongly aerated industrial waste waters mainly arrive.

The effects of water mass aeration on the heat and mass exchange at the air-water interface are under investigation at the Faculty of Physics of the Moscow State University and at the Institute of Oceanology of the Russian Academy of Sciences.

In the present paper we discuss the results of the laboratory experiments carried out under the conditions when the temperature of water was higher than that of air. We studied the temperature distribution in the ± 2-cm boundary layer at the air-water interface. The measurements in the water and air layers 0.1 cm thick, immediately adjacent to the water surface, were taken every 0.02 cm, which allowed us to reliably determine the temperature gradients at the water-air interface. At $|z| > 0.1$ cm, the measurements were taken in larger increments, and the layer with inverse temperature distribution, typical of free convection in the near-the-water air layer was not traced.

It was shown [1] that under the conditions of free convection the vertical distributions of air temperature $t_a(z)$ over aerated water differ from similar distributions over heated hard surfaces and well-matured (nonaerated) water masses. The distinction is the more noticeable the higher is the water aeration degree. As a common practice [2], the profiles are compared using the dimensionless coordinates

$$z^+ = \frac{z}{\delta_t}, \quad \delta_t = c_{pa}\rho_a k \Delta t_{sa}/Q_a, \quad t_a^+ = [t_a(z) - t_\infty]/\Delta t_{sa}, \tag{1}$$

where Q_a is the density of the contact heat flux in the air, k is the molecular thermal diffusivity, c_{pa} and ρ_a are the specific heat under constant pressure and the air density, t_s and t_∞ are the temperatures of the water surface and the ambient air, and $t_{sa} = (t_s - t_\infty)$.

Investigating the effect of aeration on a water basin heat and mass losses, one needs a quantitative measure of the degree of water mass aeration. The following estimate could be suggested [3]. We consider aerated water as a bicomponent medium in which the mass flux is due to thermal effects

$$M_Q = \frac{Q_w \alpha_w}{c_{pw}} \tag{2}$$

and to the presence of gas bubbles

$$M_a = \rho_a N_a V_a. \tag{3}$$

Here M_Q and M_a are the mass flux densities, Q_w is the density of heat flux from water to air, α_w is the thermal expansion coefficient of the fluid, c_{pw} is the specific heat of water at constant pressure, N_a is the number of gas bubbles passing through unit area in unit time, and V_a is the volume of a gas bubble.

Taking (2) and (3) into account, the mass flux density can be expressed as

$$<\rho' w'> = \left(\frac{\alpha_w}{c_{pw}}\right) Q_w + \rho_a N_a V_a = \left(\frac{\alpha_w}{c_{pw}}\right) Q_w [1 + B_1],$$

where $B_1 = M_a/M_Q$, w' is the pulsation of vertical velocity. The quantity B_1 is the ratio of the mass flux density in the bubbles to the convective mass flux, which is due to the water overheating with respect to the air. The values of B_1 determined from experimental data [3] are of the same order as the Bowen number in the near-the-water air layer (in our experiments B_1 varied from 0.02 to 0.15).

The technique used in our experiments [3, 4] allowed us to evaluate the density of the heat flux from water $\Delta Q_w^* = Q_w - Q_{w0}$, which is due to the gas bubbles release (here Q_w and Q_{w0} are the heat flux densities in aerated and nonaerated water, other conditions being equal), and the flux density of moisture M_w in the form of microspray formed by the gas bubbles released from the water. The quantity M_w can be represented as $M_w = \rho_w N_w V_w$, where ρ_w is the water density, N_w is the number of microspray formed over unit area in unit time, and V_w is the volume of a microdrop. Assuming that the collapse of a bubble at the air–water interface gives rise to a single microdrop, i.e., that $N_a = N_w$, we have

$$\frac{M_a}{M_w} = \frac{\rho_a}{\rho_w} \left(\frac{d_a}{d_w}\right)^3,$$

where d_a and d_w are the gas bubble and the microdrop diameters. Since for the conditions of our experiments we may assume that $d_a/d_w = 10^3$ and $\rho_a/\rho_w \cong 10^{-3}$, then $M_a \cong M_w$.

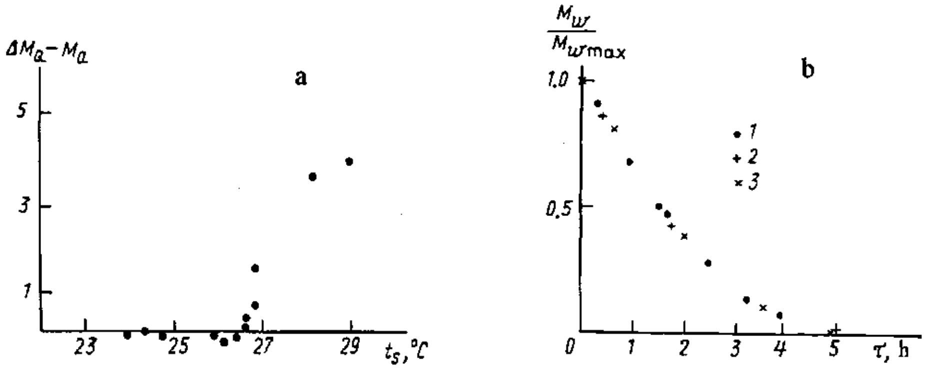

Fig. 1

Difference of ΔM_Q and M_a as a function of water surface temperature t_s (*a*); ratio $M_w/M_{w\,\max}$ as a function of time τ (*b*) for three series of measurements (symbols *1* to *3*).

The difference of mass flux densities $\Delta M_Q = \Delta Q_w^* \alpha_w / c_{pw}$ and M_a as a function of the water surface temperature (Fig. 1*a*) shows that they are equal until the water surface temperature reaches 26.5 °C. Then the total mass flux can be written in the form

$$M = M_Q + M_a = M_{Q0} + \Delta M_Q + M_a \cong M_{Q0} + 2M_a \cong M_{Q0} + 2M_w,$$

where M_{Q0} is the mass flux density (the density deficit) in water under free thermal convection without aeration.

It is of interest to compare the vertical temperature distributions $t_a(z)$ in the near-the-water air layer over aerated and mature, i.e., knowingly nonaerated, water at fixed values of the water temperature in the basin, as well as the temperature and humidity of the ambient air. Freshly poured in tap water was used as aerated water. The experiments began at the moment when the water became transparent and no dynamic changes could be visually traced in it. Preliminary tests showed that the aeration of such water decreases relatively slowly, and disappears in five hours. The results of the experiments are shown in Fig. 1*b*, where the time τ is plotted along the abscissa axis and the density of the water flux carried by microdrops, M_w, is plotted along the ordinate axis.

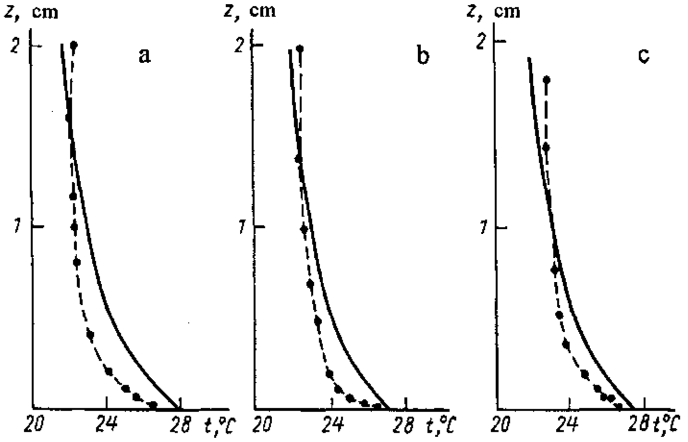

Fig. 2

Vertical temperature profiles in the near-the-water air layer over nonaerated (solid curves) and aerated (dots) water (the air relative humidity is $\varepsilon = 55\%$). The profiles were measured at consecutive moments of time.

It is difficult to obtain experimental temperature profiles simultaneously over aerated and mature water in exactly identical conditions. Therefore the following technique was employed. As shown in [1], the vertical temperature distribution over a heated water surface under free convection and with nonaerated water is calculated by the formula proposed in [2]. However, the calculations require that in addition to water and air temperatures (t_w and t_a), the water surface temperature t_s and the contact heat flux density Q_a (see (1)) be given. A closed set of equations given in [5] was used for calculating the values of t_s and Q_a. Figure 2 shows the experimentally measured vertical temperature distributions over water of different degrees of aeration (black dots), along with the temperature profiles $t_a(z)$ over nonaerated water, under the same conditions as in the case of aerated water calculated by the technique described above. The parameter B_1 which we use for characterizing the degree of water mass aeration is 0.06 for Fig. 2*a*, 0.04 for Fig. 2*b*, and 0.02 for Fig. 2*c*.

As is seen from Fig. 2, the air temperature in a thin near-the-water air layer over aerated water, if the air relative humidity is smaller than 100%, is noticeably lower than over nonaerated water. The thickness of this "cooled" layer increases with the value of B_1. In the first case (Fig. 2*a*), the air is cooled up to a height of 16 mm over the water level, in the second case to 14 mm (Fig. 2*b*), and in the third case to 10 mm (Fig. 2*c*). Thus, the heat content of a thin near-the-water air layer is the lower the greater the value of B_1, i.e., the higher the degree of water aeration. With the aid of Fig. 2 and similar graphs, it is easy to calculate the heat content reduction ΔS in the thin near-the-water air layer over heated aerated water relative to nonaerated water. The results of such calculations, shown in Fig. 3, demonstrate that ΔS grows with increasing water aeration.

It must be noted that the air temperature above the cooled layer over aerated water is somewhat higher than over nonaerated water (see Fig. 2).

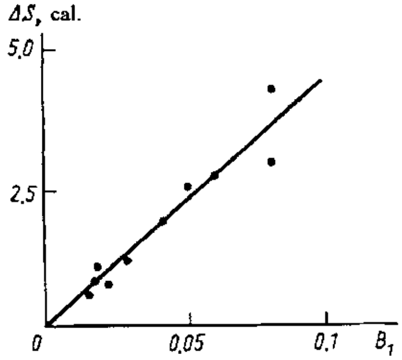

Fig. 3

Heat content deficit ΔS in a thin near-the-water air layer as a function of parameter B_1.

The thermal processes in the near-the-water air layer under the conditions of free convection and in the presence of drop-bubble exchange can be described in the following way. If the air is not saturated with water vapor ($\varepsilon < 100\%$), the drops released from the water as a result of gas bubble collapses will evaporate, removing heat from the thin near-the-water air layer. Consequently, the water surface will also cool, which will lead to an increase of the water temperature gradient near the interface $dt_w/dz|_{z\to 0}$ and to a growth of the heat flux from the water into the atmosphere.

This study was supported by the Russian Foundation for Basic Research (Grant 95-05-14689).

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24 May 1996

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