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Numerical Modeling of the Influence of Cool Skin on the Heat Balance and Thermal Regime of a Water Body

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Abstract—The influence that cool skin has on the energy exchange between the atmosphere and the ocean is investigated in this work. For this purpose, a series of numerical experiments with the use of the one-dimensional LAKE model of a water body were performed. Three types of cold-skin parameterization were used in this model. The data of in situ measurements in the coastal zone of the Black Sea, in the Arctic Ocean, and over Lake Sparkling served as the boundary and initial conditions. It has been established from the results of experiments that the LAKE model with the incorporated parameterization of the cool skin successfully reproduces cold-skin characteristics, namely, the difference between the temperature of the cool skin surface and the water temperature below the skin. The results of numerical experiments are within the variability of the results of in situ measurements. It has been shown that the presence of a cool skin reduces the heat losses of a body of water. The numerical experiments showed that the presence of a cool skin can change the thermal regime of a water body and its stratification by changing the heat balance at the surface. This result can be important for the modeling of many processes inside a body of water and at its surface, for example, gas and heat exchange.

Key words: numerical modeling, ocean–atmosphere interaction, heat balance of bodies of water, cool skin.

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1. INTRODUCTION

For solving various applied and fundamental problems of the atmospheric physics, it is necessary to estimate the processes of energy exchange at the atmosphere–ocean interface. In this respect, information about the surface temperature of the water is of a key importance, because it is the difference between this temperature and the air temperature that largely controls the intensity and direction of exchange processes. The surface temperature of the ocean is used for determining the heat balance components at the ocean surface: turbulent fluxes of heat and moisture, as well as the outgoing long-wave radiation. The gas exchange between the atmosphere and the ocean also, to a considerable degree, depends on the surface temperature.

The cold-skin phenomenon at the surface of the ocean and bodies of water on the land has been investigated for several decades. Numerous in situ experiments have shown that a thin layer less than 1 mm thick is present at the surface of the ocean. In this layer, the profile of the water temperature is characterized by its linear change (as a rule, its increase) with depth. In this connection, the term "cool skin" was introduced. Many authors [1–4] define the cool skin as a thin layer on the surface of the ocean where molecular heat exchange is the dominating mechanism of energy transfer. According to the data of in situ experiments, the difference between the cold-skin temperature and the water temperature in the near-surface layer varies within the range of –0.1 to –2.0°C [4–7].

cool skin is a structure that is stable in time and space and can be observed everywhere in the ocean [8]. Nevertheless, in various studies, in various estimates, the water temperature T_{bulk} at a certain depth of measurements is usually assumed to be the ocean-surface temperature. In numerical modeling, the mean temperature of the closest to the surface layer of the finite-difference grid is taken as the ocean-surface temperature. This leads to systematic errors in determining the temperature of the ocean surface, which in turn leads to errors in estimates of the atmosphere–ocean heat exchange.

The cold-skin effect is taken into account when problems of the operational weather forecast are solved, which is dictated by the necessity to correctly interpret data from satellite measurements. The ocean-surface temperature measured from satellites in the infrared and microwave regions is the cold-skin temperature [4]. Therefore, the cold-skin parameterization is already used, in particular, in the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) for the operational weather forecast [9].

By now there have been performed some studies [3] of the influence of cool skin on the heat balance at the ocean surface that were based on short-term numerical experiments when data of in situ measurements were available. The results obtained in [3] show that, if the cool skin is taken into account, this will lead to a systematic decrease in the calculated heat and moisture fluxes at the surface of the ocean by about 10%. The influence of the cool skin on the heat balance at the water surface, although it is expressed in its relatively small changes (by about 10 W/m^2 [3]), is of a systematic character, which suggests that, on long time intervals, the cold-skin effect will accumulate, causing substantial changes in the thermal regimes of the ocean and bodies of water on the land. Nevertheless, as far as we know, the cool skin is not presented in existing climatic models, and the question concerning the effect of its parameterization on the model climate remains an open question.

In order to estimate the necessity of taking into account the cool skin, when the processes of interaction between the atmosphere and ocean are modeled on long time intervals, we performed a number of numerical experiments with the one-dimensional model of body of water LAKE [10]. For solving this problem, we incorporated several parameterizations of the cool skin into the LAKE model: the Fairall [3] and Saunders [11] parameterizations, as well as a simplified parameterization, when the thickness of the cool skin is specified by a constant. In order to make sure that the LAKE model with the incorporated parameterization is capable of realistically reproducing the cold-skin phenomenon under different meteorological conditions, we performed a series of numerical experiments on short time intervals (several days long) with the use of the results of meteorological and oceanological measurements in the coastal zone of the Black Sea and in the Arctic. Experiments on long time intervals were also performed for Lake Sparkling (Wisconsin, United States) from May to September over 2002–2005. In this case the observational data obtained in the course of the North Temperate Lakes LTER project were used [18]. Comparing the results of numerical experiments while allowing for the cool skin with the results of control experiments without regard for the cool skin, we estimated the influence of the cool skin on the heat-balance components at the surface of a body of water and considered the influence of the cool skin on the thermal regime of Lake Sparkling. The results of numerical experiments proved to be in compliance with the results of in situ measurements presented by many authors [4–7].

2. THE LAKE MODEL OF A BODY OF WATER

The one-dimensional LAKE model of a body of water [10] is being developed at the Research Computating Center of Lomonosov Moscow State University (MSU). The thermodynamic regime of the water body in this model is described with the use of the one-dimensional heat conduction equation with the heat source based on the absorption of short-wave solar radiation. Since the level of the body of water changes over time due to precipitation and evaporation, the vertical coordinate is introduced $\xi = \frac{z}{h}$, which varies within the range [0, 1], because $h = h(t)$ is the depth of the water body as a function of time, and z varies within the range $[0, h]$. This allows to introduce a fixed irregular grid and a constant integration domain. For calculating the solar-radiation flux, we use the exponential dependence of the flux on the depth in this model:

$$S(\xi) = (1 - A)(1 - \beta_e) S \exp(-\alpha_e h \xi), \tag{2.1}$$

where S is the total solar radiation at the surface of the water body, A is the water-surface albedo, α_e is the extinction ratio characterizing water turbidity and taking the values from several tenths to several units of m^{-1}, and β_e is the fraction of solar radiation absorbed by a thin skin at the surface of the water body.

There are several variants of the parameterization of turbulent heat exchange in the LAKE model:

(i) the "empirical" parameterization proposed in [10];

(ii) parameterization on the basis of the equation of kinetic energy of turbulence with the use of a specified profile of the integral turbulence scale;

(iii) parameterization on the basis of the equations of balance of the kinetic energy of turbulence and its dissipation rate (the k-ε or E-ε parameterization);

(iv) semiempirical parameterizations diagnostically relating the coefficient of turbulent exchange to the Richardson number and some other parameters. In this work, we use the E-ε parameterization, because, in the presented list, it is most sensible from the physical standpoint and seems to be applicable to the widest range of turbulent flows.

To determine the depth of the water body, the equation of the water balance is solved in the following form:

$$\frac{dh}{dt} = r - E_S - R_S - R_b, \tag{2.2}$$

where r is the intensity of precipitation, E_S is the evaporation rate, R_S is the sink controlled by discharges of tributaries and effluent streams, and R_b is the water exchange between the water body and the underlying ground.

If a water body is covered by ice and snow, the heat and moisture transfer in the snow cover and the heat exchange in the ice layer are described in the model with the use of the heat conduction equation with the radiation source. The model of the snow cover explicitly takes into account the transfer of the liquid moisture [12]. Additionally, the model based on the equations of the diffusion type with the sources of phase transitions describes the heat and moisture transfer in the ground layer beneath the water body.

For calculating the upper boundary condition of water, ice, and snow cover, the heat balance equation is used in the LAKE model:

$$E_a - E_s - H_s - LE = -\frac{k_T}{h}\frac{\partial T}{\partial \xi}, \tag{2.3}$$

where E_a is the atmospheric longwave counterradiation, E_s is the radiation emitted by the water surface, H_s and LE are the fluxes of sensible and latent heat (the upward directions are positive), and k_T is the coefficient of turbulent heat conductivity. The water-surface albedo depends on the sun elevation angle h_0 and is calculated in the model by the formula

$$A = \frac{0.05}{\sin h_0 + 0.15}. \tag{2.4}$$

In our numerical experiments, we corrected the water-surface temperature calculated on the basis of the numerical solution of (2.3) for the presence of the cool skin in accordance with the Fairall parameterization of the cool skin [3], which will be described below.

To calculate the turbulent fluxes of heat and moisture in the surface air layer in the LAKE model, it is possible to use one of two parameterizations:

(1) The aerodynamic method with the exchange coefficients calculated in accordance with the Monin–Obukhov similarity theory. In this case, it is supposed that profiles of meteorological parameters are specified in surface layer according to flux-gradient relationships proposed by Businger, Beljaars and others [13, 14].

(2) The Louis parameterization [15], which is also based on the Monin–Obukhov similarity theory. As opposed to the preceding scheme, vertical profiles of meteorological parameters are determined here as dependent on the Richardson number.

In this study, we use the first parameterization.

The model equations are numerically solved on a staggered grid, where the turbulent kinetic energy, rate of its dissipation, and coefficients of turbulent exchange are calculated in center points of the grid cells and the temperature, salinity, and flow-velocity components are calculated in points at the grid cells' faces.

The number of points along the coordinate ξ and the integration time step are specified arbitrarily, provided that the finite-difference scheme is stable.

The surface temperature, temperature profile in the water body, temperature of the underlying ground, and temperature profile in the ground are specified as the initial data for the model. The atmospheric forcing (air temperature and humidity, wind speed, and atmospheric pressure at a certain height in the atmospheric surface layer, as well as the total solar radiation and counterradiation of the atmosphere) is specified as the boundary conditions over the period of model integration with respect to time.

In the numerical experiments for different types of lakes located in contrasting climatic conditions (Lake Vendyurskoe (Karelia), thermokarst lake in the Tiksi area, Mozhaisk water storage reservoir, Lake Kossenblatter (Germany; the data are kindly provided by Deutscher Wetterdienst (Meteorologisches Observatorium Lindenberg—Richard-Aβmann-Observatorium)) Alkjeva water storage reservoir Portugal, etc.), the model demonstrated satisfactory agreement with observational data on the surface temperature and the heat exchange between the atmosphere and the lake surface. This model is taking part in the international LakeMIP project (Lake Model Intercomparison Project) [16].

Since the horizontal dimensions of a water object are not included in the one-dimensional formulation of the problem solved in the LAKE model, this model can be applied both for inland bodies of water and for reproducing the boundary layer of the ocean.

3. PARAMETERIZATION OF THE COOL SKIN

The temperature increase with depth within the skin is explained by the fact that the heat losses with evaporation and long-wave radiation take place at its surface. These processes maintain the existence of a temperature gradient inside the skin. Taking into account the contact heat exchange with the atmosphere, the total heat losses at the water–air interface can be presented in the form

$$-Q = R_{nl} - H_s - LE, \tag{3.1}$$

where $R_{nl} = E_a - E_s$ is the balance of long-wave radiation, E_a is the counterradiation of the atmosphere, E_s is the longwave radiation emitted by the water body, H_s is the turbulent flux of sensible heat (the upward direction is positive), and LE is the turbulent flux of latent heat (the upward direction is positive).

In this case, the temperature gradient T in the cool skin, which is controlled by the process of molecular heat conductivity, is expressed in the following way:

$$k\frac{\partial T}{\partial z}\bigg|_{z=0} = Q, \tag{3.2}$$

where k is the coefficient of molecular heat conductivity for water and the axis z is directed downward.

At some depth, turbulent mixing starts to dominate over the molecular heat exchange; this depth is the lower boundary of the skin.

The difference between the surface temperature of the cool skin T_{skin} and the water temperature at some depth T_{bulk},

$$\Delta T_{skin} = T_{skin} - T_{bulk}.$$

is of major interest.

According to the data of numerous in situ measurements, the value of ΔT_{skin} varies from –0.1 to –2°C, taking its mean values within the range of −0.3…−0.4°C [4–7]. Many authors note the inverse dependence of the ΔT_{skin} modulus on the wind speed [4, 7, 17]. If the wind speed increases, the skin becomes thinner and ΔT_{skin} decreases, asymptotically approaching a certain small value. Thus, it is noted in work [4] that if wind velocities exceed 6 m/s, it can be assumed that $\Delta T_{skin} = -0.17 \pm 0.07$°C.

If we assume that T_{bulk} is the temperature at the depth δ corresponding to the lower boundary of the cool skin, formula (3.2) can be rewritten in the following form:

$$k\frac{T_{skin} - T_{bulk}}{\delta} = -Q \tag{3.3}$$

or

$$\Delta T_{skin} = -\delta\frac{Q}{k}. \tag{3.4}$$

It can be seen from formula (3.4) that the temperature drop in the skin depends both on the intensity of heat losses from its surface and on the skin thickness δ. The thickness of the cool skin depends on the intensity of turbulent mixing in the ocean surface layer. Therefore, the value of ΔT_{skin} varies both in time and space depending on the hydrometeorological conditions. The wind speed and the temperature difference between the water surface and air are the decisive parameters.

The Fairall [3] parameterization is used as the basic parameterization in the LAKE model. Fairall [3] improved the Saunders [11] parameterization by taking into account the relations of free convection and shear turbulence regimes for an estimation of mixing in the ocean surface layer. The explicit accounting for the mixing regime is necessary for an adequate determination of the thickness of the cool skin. Fairall specifies the thickness of the cool skin in the following way:

$$\delta = \frac{\lambda\nu}{(\rho_a/\rho_w)^{1/2}u_{*a}}, \tag{3.5}$$

where ν is the kinematic viscosity of water, ρ_a is the atmospheric air density in the near-water layer, ρ_w is the water density in the near-surface layer, u_{*a} is the friction velocity in the atmosphere, and λ is a dimensionless coefficient. Through λ, the mixing regimes caused by free convection and shear turbulence are jointly taken into account in the near-surface layer of the water body.

The following formula is proposed for calculating the coefficient λ:

$$\lambda = \lambda_0\left[1 + \left(\frac{\lambda_0^4 A_0^3 Q_b g\alpha\rho_w c_p\nu^3}{u_{*a}^4(\rho_a/\rho_w)^2 k^2}\right)^{3/4}\right]^{-1/3}, \tag{3.6}$$

where λ_0 is the dimensionless Saunders constant, for which Fairall, as well as Saunders, proposes that the value 6 be used; A_0 is the dimensionless empirical constant equal to 0.23; α is the coefficient of thermal expansion; g is the gravitational acceleration; c_p is the specific heat capacity of water at constant pressure; k is the coefficient of the molecular heat conductivity of water; and Q_b is the heat flux through the surface, including the effect of density mixing due to salinity changes during evaporation (virtual heat flux):

$$Q_b = Q + \left(\frac{S_m\beta c_p}{\alpha L}\right)LE, \tag{3.7}$$

where S_m is the mean salinity at the water surface, β is the coefficient of expansion due to salinity changes, and L is the heat of evaporation.

The Fairall idea states that, if the wind speed increases, the value of the coefficient λ tends to λ_0, which corresponds to the conditions of mixing due to shear turbulence; if the wind speed decreases, the increasing contribution of the free-convection mechanism to the skin thickness is taken into account through the coefficient λ.

Therefore, determining the thickness of the cool skin by formulas (3.5) and (3.6), it is possible to calculate the value of ΔT_{skin} with the use of relation (3.4).

When calculating the temperature of the skin, it is necessary to take into account the absorption of solar radiation in the skin. If δS_c is defined as the mean value of the solar-radiation flux absorbed in the sublayer of the cool skin, we, following Fairall, substituted $Q - \delta S_c$ for the heat loss at the skin surface Q in formulas (3.2)–(3.4), when the heat losses from the skin surface were described. The solar radiation absorbed in the skin layer was specified as $\delta S_c = f_c S$, where f_c in a fairly general form can be expressed as follows:

$$f_c = f(\delta) = \sum_{i=1}^{N} F_i\left\{1 - \frac{\gamma_i}{\delta}[1 - \exp(-\delta/\gamma_i)]\right\}, \tag{3.8}$$

where f_c is the function, which describes the absorption for nine bands of different wavelengths from the solar radiation spectrum with the amplitude F_i and the absorption path γ_i; S is the total flux of solar radiation, W/m^2. The first four bands have absorption paths much longer than 1 mm, and the last four bands have absorption paths much shorter than 1 mm. This allows us to approximate the mean absorption in the sublayer ($\delta < 1$ cm) in the following way:

$$f_c = 0.137 + 11\delta - \frac{6.6 \times 10^{-5}}{\delta} - \{1 - \exp[-\delta/(8 \times 10^{-4})]\}, \tag{3.9}$$

where 0.137 is the sum of the last five values of F_i and 11 is the half-sum of the first four values of the quantity F_i/γ_i.

Fairall [3] notes that, at wind velocities lower than 1 m/s, the radiation absorbed in the layer δ can exceed the total cooling Q described by formulas (3.2)–(3.4). In this case, usually at about noon, the cool skin can be absent and a warm skin can even be observed [3]. The appearance of the warm skin under certain conditions was also noted by other authors [22].

Along with the Fairall parameterization, we used the Saunders parameterization [11], which differs from the former by the coefficient λ, which is specified by the constant equal to 6 in formula (3.5). The shortcoming of the Sounders parameterization manifests itself at low wind velocities. It can be seen from formula (3.5) that, when λ is a constant, the skin thickness δ starts to grow infinitely if the wind speed decreases, which necessitates the introduction of a certain limitation for the skin thickness.

Equation (3.4), where the skin thickness δ was specified by the constant equal to 1 mm, was used as a maximally simplified parameterization.

The numerical parameterization scheme of the cold-skin effect in the LAKE model of a water body that we used is based on a search for the temperature of the cool skin at which the residual of the heat balance equation for the skin does not exceed a specified small value. This temperature is found in the course of the iterative process with the use of the false position method.

4. NUMERICAL EXPERIMENTS

The main problem of numerical experiments was the study of the contribution of the cool skin to the heat-balance components at the surface of a water body, namely, to the turbulent fluxes of heat and moisture in the atmospheric surface layer, as well as to the flux of longwave radiation emitted by the surface of a water body.

A series of numerical experiments with the LAKE model were performed for both relatively short time intervals on the order of several days and prolonged time intervals of about five months.

Since the skin parameters depend, to a considerable extent, on the atmospheric conditions in the near-water air layer, numerical experiments with different initial data, boundary conditions, and model parameters, performed under different geographic conditions, were based on the data of three in situ experiments:

(1) measurements at the coastal station in Feodosiya Bay (Black Sea) in June 2008;

(2) measurements at the edge of the poynya (an open water area in the sea ice field) in the Laptev Sea (Arctic) in September 2005 at a point with the coordinates 79.9° N and 142.5° E (the expedition on board the *Kapitan Dranitsyn* ice breaker within the framework of the NABOS project);

(3) long-term measurements on Lake Sparkling (Wisconsin, United States) in 2002–2005 [18].

Control numerical experiments without regard for the cool skin and numerical experiments with the incorporated parameterization of the skin were conducted in each case. All of the three cold-skin parameterizations described above were considered in the numerical experiments based on observational data obtained in the Black Sea and the Arctic. The Fairall parameterization alone was used in the numerical experiments based on the data of [18], because this parameterization most adequately reproduces the thickness of the cool skin in the wide range of wind velocities.

First and foremost, it was necessary to make sure that the LAKE model with the incorporated cold-skin parameterization successfully reproduces the quantity ΔT_{skin}. Then, comparing the results of control experiments and experiments with the incorporated cold-skin parameterization, we obtained the response of other variables of the model to the cold-skin inclusion, which allowed us to estimate the influence that the presence of cool skin has on the heat-balance components at the surface of a water body. In the numerical experiments in Lake Sparkling with the use of long-term data, we also estimated the influence of cool skin on the thermal regime of this water body.

5. INITIAL AND BOUNDARY CONDITIONS

It was necessary to specify the vertical distributions of water temperature and salinity as the initial conditions for each experiment with the LAKE model. While all the hydrologic observation data necessary for the specification of initial conditions were available in the case of Lake Sparkling, only the data of temperature and salinity measurements at the surface were at our disposal for the Black Sea and the Arctic.

In Feodosiya Bay, the vertical profile of the temperature was specified as the mean profile of the seawater temperature for June [19]. The vertical distribution of salinity was specified as constant and equal to 17‰. The specified depth was 10.5 m. The data of standard meteorological observations in the period of June 22–27, 2008, averaged over half-hour intervals were used as the boundary conditions.

Table 1. Temperature difference between the cool skin and water at a depth of 0.5 m ($\Delta T_{skin} = T_{skin} - T_{bulk}$), °C, in Feodosiya Bay (Black Sea) from the results of numerical experiments

Temperature difference, °C	Difference value	Experiment F	Experiment S	Experiment C
$\Delta T_{skin} = T_{skin} - T_{bulk}$	Mean	–0.26	–0.36	–0.17
	Minimal	–0.44	–0.90	–0.49
	Maximal	0.08	0.19	–0.06

For the second series of experiments, the data of meteorological measurements at the edge of the polynya in the Arctic at the point with the coordinates 79.9° N and 142.5° E in the period September 16–19, 2005, were used as the boundary conditions for the LAKE model. The flux of long-wave counterradiation was calculated in both cases by the Brunt formula [20]. The total radiation during the Arctic experiment was reconstructed from the NCEP/NCAR reanalysis data. The specified depth of the water body was 40 m, because, on a scale of several days, processes at larger depths have no substantial influence on the surface state. The near-surface layer in basins of the Arctic Ocean with reduced salinity and depths of several tens of meters is well-mixed and called the polar mixed layer (PML). Being guided by these considerations and based on water temperature measurements, we presented the initial temperature profile in this experiment as the constant –1.0°C and the salinity profile as the constant 33‰ to a depth of 40 m.

6. REPRODUCTION OF THE COOL SKIN IN THE BLACK SEA AND THE ARCTIC AND ITS INFLUENCE ON HEAT-BALANCE COMPONENTS AT THE OCEAN SURFACE

For the Black Sea and the Arctic, the following series of numerical experiments were performed.

(1) The control experiment without regard for the cool skin.

(2) Experiment C with the constant thickness of the cool skin equal to 1 mm during the entire experiment.

(3) Experiment S with the use of the Saunders parameterization.

(4) Experiment F with the use of the Fairall parameterization.

As it is noted above, the difference between the skin temperature and the water temperature in the near-surface layer ($\Delta T_{skin} = T_{skin} - T_{bulk}$) is of greatest interest. For the Black Sea, the mean, maximal, and minimal differences between the cold-skin temperature and the mean water temperature in the upper layer of the model 0.5 m thick are given in Table 1 for each experiment.

The least in modulus mean over the period of experiments value of ΔT_{skin} was reproduced when the skin thickness was specified by a constant and was equal to –0.17°C. The greatest in modulus mean value of ΔT_{skin} was obtained during the experiment when the skin thickness was specified in accordance with the Saunders approach and was equal to –0.36°C. In the experiment with the use of the Fairall parameterization, the mean value of ΔT_{skin} was –0.26°C. These results are comparable with the results obtained by different authors from observational data [4–7]. The maximal in modulus instantaneous values of ΔT_{skin} were obtained in experiment S: –0.9°C, which is twice as large as the maximal in modulus values obtained in experiment F: –0.44°C.

The plots reflecting the dependence of ΔT_{skin} on the wind speed in accordance with the results of numerical experiments are presented in Fig. 1. It can be seen that the Fairall and Saunders parameterizations reflect the above-mentioned tendency of ΔT_{skin} to grow in modulus when the wind speed decreases.

The values of ΔT_{skin}, obtained with the use of the Saunders parameterization exceed the corresponding values obtained with the use of the Fairall parameterization. It can be seen from Fig. 1 that the largest differences were obtained at low wind velocities (less than 3–4 m/s). This result would be expected because, as noted above, the Fairall parameterization is characterized by a more correct presentation of the cool skin exactly at low wind velocities. Nevertheless, the values of ΔT_{skin} in the experiments with the use of both parameterizations lie within the variability of the results of in situ observations given in the literature.

The presented results of numerical experiments suggest that the LAKE model with the incorporated Fairall and Saunders parameterizations makes it possible to realistically reproduce the cold-skin temperature at different wind velocities.

Since it is the surface of the cool skin that takes part in the heat exchange with the atmosphere, the presence of the cool skin contributes to the turbulent fluxes of heat and moisture in the near-water layer, also affecting the flux of outgoing long-wave radiation. Thus, the cool skin has an influence on the heat bal-

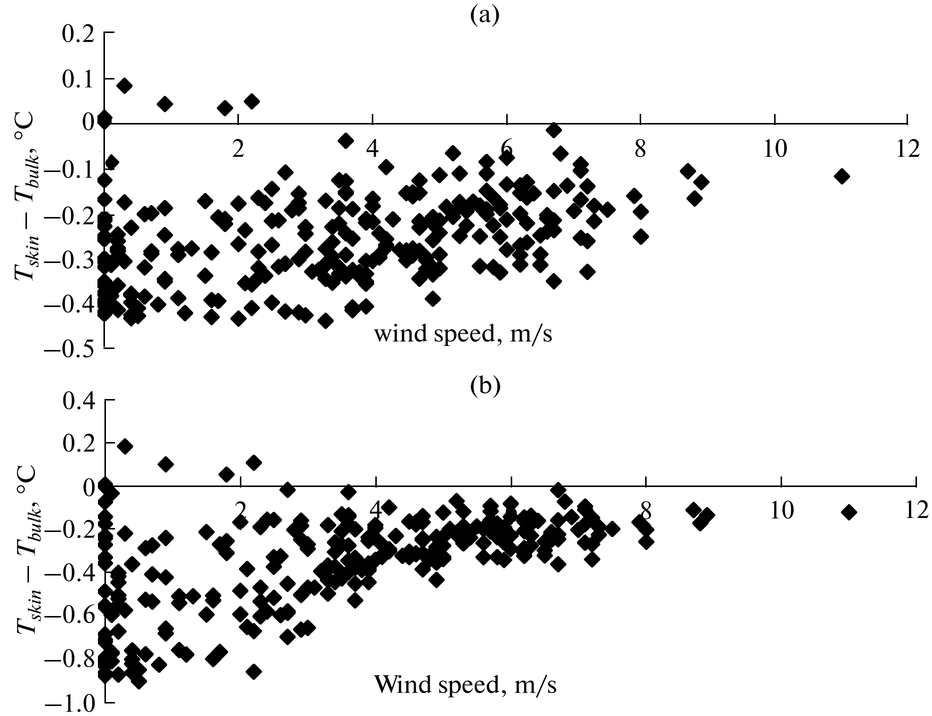

Fig. 1. Dependence that the temperature difference between the skin and water at a depth of 0.5 m, ΔT_{skin} has on the wind speed at the measurement height (21 m) for (a) Fairall (experiment F) and (b) Saunders (experiment S) parameterizations of the cool skin.

ance at the surface of a water body. This balance can be written in the following way:

$$B = -S(1 - A) + H_s + LE + E_{eff}, \qquad (6.1)$$

where S is the total solar radiation; A is the water-surface albedo; H_s and LE are the turbulent fluxes of sensible and latent heat, respectively; and $E_{eff} = E_s - E_a$ is the so-called “effective radiation” – the difference between outgoing longwave radiation E_s and counter-radiation of the atmosphere E_a. Therefore, negative values of the heat balance at the lake surface correspond to the heat flux directed from the atmosphere into the water body, which leads to its heating.

Numerical experiments allowed us to estimate the influence of cool skin on the heat-balance components in the Black Sea (Table 2).

The inclusion of the cold-skin effect into the numerical experiment most strongly affected the latent heat flux. In the experiments with allowance for the skin, the latent-heat flux was, on average, 2.5–3.0 W/m^2 smaller than in the experiment without regard for the skin. This makes to 7–9% of the average latent heat flux, computed in these experiments.

With allowance for the cool skin, the sensible-heat flux changed little: it decreased by 0.2–0.3 W/m^2, which amounts to about 5% of its mean value. The outgoing longwave radiation also changed insignificantly (it decreased by 0.6–1.0 W/m^2) with allowance for the cool skin. The total contribution of the cool skin to the heat balance at the sea surface was 3.5–4.5 W/m^2 toward the heat flow decrease from the sea into the atmosphere. It is important to note that such an influence of the cool skin on the heat-balance components

Table 2. Heat-balance components at the surface of Feodosiya Bay (Black Sea) averaged over the time of numerical experiments

Experiment	Sensible-heat flux (W/m^2)	Latent-heat flux (W/m^2)	Effective radiation (W/m^2)	Heat balance at the surface (W/m^2)
Without regard for the cool skin	−6.4	38.2	75.6	−143.1
Experiment C	−6.7	35.7	75.1	−146.4
Experiment S	−6.6	35.1	74.5	−147.4
Experiment F	−6.6	35.7	74.9	−146.4

Table 3. Temperature difference between the cool skin and water at a depth of 1.5 m in the polynya in the Arctic from the results of numerical experiment

Temperature difference, °C	Difference value	Experiment F	Experiment S	Experiment C
$\Delta T_{skin} = T_{skin} - T_{bulk}$	Mean	–0.31	–0.32	–0.53
	Minimal	–0.51	–0.55	–0.81
	Maximal	–0.07	–0.07	–0.21
	rms	0.07	0.08	0.12

at the surface of the water body was of a systematic character throughout the experiments.

The mean and extreme values of the temperature difference between the skin and water at a depth of about 1.5 m (corresponding to closest to the surface level of the model ($\Delta T_{skin} = T_{skin} - T_{bulk}$), which were obtained in the experiments, are presented in Table 3.

The greatest in modulus mean value of ΔT_{skin} was obtained in experiment C, when the skin was specified by a constant, and was equal to –0.53°C. The results of experiments F and S differ insignificantly: the mean values of ΔT_{skin} were –0.31 and –0.32°C, respectively; the maximal and minimal values of ΔT_{skin} also differed only slightly. These results are explained by the relatively high wind speed throughout the entire experiment, because the substantial distinction of the Fairall parameterization from the Saunders parameterization consists exactly in the specification of the skin thickness at weak winds. If these results are compared with the modeling of Feodosiya Bay in the Black Sea, the value of ΔT_{skin} in experiment C for the Arctic will exceed in modulus the corresponding values for the Black Sea by about three times. If the mean value of ΔT_{skin} in experiment C was the least value compared with experiments F and S for the Black Sea, for the Arctic, on the contrary, the values of ΔT_{skin} in experiment C exceed the corresponding values in the other experiments. These results are associated with the fact that, by specifying the skin thickness by a constant, we do not take into account the effect of thinning and the breakdown of the skin at the wind speed increase; consequently, at the high wind velocities observed in the Arctic, we obtain overestimated in modulus values of ΔT_{skin}.

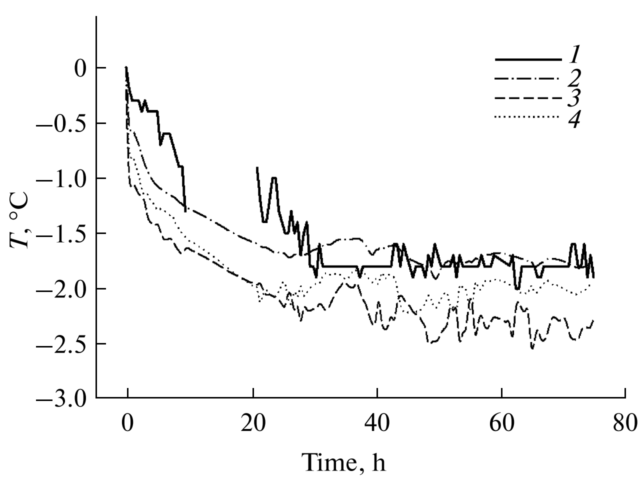

Fig. 2. Water temperature at the polynya surface, °C, from the data of measurements and numerical experiments: (*1*) data of measurements, (*2*) control experiment, (*3*) experiment C, and (*4*) experiments F and S (curves almost completely coincide).

The curves of water temperature measurements in the polynya and the model data on the surface water temperature obtained in the control experiment, as well as the cold-skin temperature, are presented together in Fig. 2. The water-temperature curve obtained in the control experiment agrees well with the data of measurements. Within about 30 h from the beginning of integration, the model and measured water temperatures reach the level of values of about –1.8°C, whereupon they change only slightly. Thus, beginning at 45 h of the model time, the difference between the model and measured temperatures does not exceed 0.1°C. Such behavior indicates that the initial data and model parameters are chosen correctly, and that the heat balance at the surface and the turbulent exchange in the near-surface water layer are reproduced adequately.

It is seen from Fig. 2 that the calculated temperature of the cool skin is 0.5–1.0°C lower than the water temperature obtained from measurements, which would be expected from physical considerations.

Let us consider the contribution from the cool skin to the heat-balance elements at the polynya surface. The values of turbulent fluxes of sensible and latent heat, effective radiation, and heat balance at the surface (averaged over the time of numerical experiments) are given in Table 4.

As can be seen from this table, the largest contribution of the cool skin to the heat balance at the polynya surface and its components was obtained in experiment C. For this experiment, the mean sensible-heat fluxes proved to be 10.2 W/m^2 smaller than their values obtained in the control experiment, which amounts to

Table 4. Heat-balance components (W/m^2) at the air-hole surface averaged over the time of the experiments

Experiment	Sensible-heat flux (W/m^2)	Latent-heat flux (W/m^2)	Effective radiation (W/m^2)	Heat balance at the surface (W/m^2)
Without regard for the cool skin	124.3	66.6	126.5	260.5
Experiment C	114.1	60.4	124.3	241.9
Experiment S	118.8	63.3	125.2	250.3
Experiment F	118.9	63.3	125.2	250.5

about 8% of the sensible-heat flux. The latent-heat flux and the effective radiation in experiment C are also 6.2 (10%) and 2.2 (2%) W/m^2 smaller than their respective values obtained in the control experiment. As a result, the heat balance in experiment C is 18.6 W/m^2 smaller than in the control experiment, which means that the amount of heat lost by the ocean in experiment C is 18.6 W/m^2 smaller. The factors responsible for the greatest contribution of the cool skin to the heat balance and its components during experiment C are the same as those mentioned above in connection with the overestimated values of the quantity ΔT_{skin} at high wind velocities in this experiment.

The contributions that the cool skin makes to the heat-balance components during experiments F and S are approximately the same. The sensible-heat flux is 5.5 W/m^2 (4.5%) smaller than in the control experiment. The turbulent flux of latent heat, mean over the time of experiments, is 3.3 W/m^2 (5%) smaller than in the control experiment. The contribution that cool skin makes to effective radiation was expressed in its 1.3 W/m^2 decrease. As a result, during experiments F and S, the heat balance at the polynya surface decreased by 10.0 and 10.2 W/m^2, respectively, compared with the control experiment. As in the case of the Black Sea, a decrease in the heat flux from the ocean to the atmosphere caused by the inclusion of cool skin was observed throughout the entire experiment.

7. REPRODUCTION OF THE COOL SKIN IN LAKE SPARKLING AND ITS INFLUENCE ON THE HEAT-BALANCE COMPONENTS AT THE LAKE SURFACE AND THE THERMAL REGIME OF THE LAKE

The above-presented estimates of the influence that cool skin has on the heat-balance components at the sea and ocean surfaces toward decreasing the heat losses of the water body, as well as the systematic character of this influence throughout all numerical experiments, suggest that, at long time intervals, the presence of a cool skin can substantially change the thermal regimes of water bodies and associated processes.

The long continuous series of hydrologic and meteorological observations over the period 2002–2005 [18], which are available for Lake Sparkling (Wisconsin, United States), made it possible to perform a series of numerical experiments with the LAKE model on long time intervals.

The experiments were performed for warm periods (from the beginning of May to the end of September) of each year from 2002 to 2005. The results of control experiments without regard for the cool skin were compared with the results of experiments with the use of the Fairall parameterization.

The monthly mean values of ΔT_{skin}, obtained from the numerical experiments and characterizing the presence of the cool skin on the surface of the lake are given in Table 5.

It can be noted from this table that there is a characteristic temporal trend of ΔT_{skin}. In May and June, the monthly mean values of ΔT_{skin} are not large and vary within the range from –0.12 to –0.28°C. However, beginning from June, ΔT_{skin} grows in modulus and attains its maximum (about –0.5 to –0.55°C) in August–September. Such behavior is explained by the fact that ΔT_{skin} depends on the total heat losses at the surface of the water body Q (formula (3.4)). At the beginning of the warm period, the lake receives heat from the warmer atmosphere with the sensible-heat flux. In the second half of the warm period, the sensi-

Table 5. Monthly mean temperature differences between the cool skin and water at a depth of about 0.03 m, $\Delta T_{skin} = T_{skin} - T_{bulk}$, °C

Year	Monthly mean values of $\Delta T_{skin} = T_{skin} - T_{bulk}$, °C				
	May	June	July	August	September
2002	–0.17	–0.12	–0.42	–0.49	–0.54
2003	–0.20	–0.28	–0.42	–0.47	–0.50
2004	–0.12	–0.18	–0.35	–0.51	–0.39
2005	–0.13	–0.21	–0.43	–0.55	–0.50

Table 6. Heat balance at the surface of Lake Sparkling from May through September from the data of numerical experiments

Numerical experiment	Values of the heat balance B, GJ/m^2			
	2002	2003	2004	2005
Control experiment	−9.5	−25.2	−90.3	−54.8
Experiment with allowance for the cool skin	−12.0	−27.5	−92.6	−57.2

Table 7. Monthly mean differences between the heat balances at the surface of Lake Sparkling in the experiments allowing for the cool skin and in the control experiments without regard for the skin

Year	Monthly mean values of the difference $B_{skin} - B_{no\_skin}$, W/m^2				
	May	June	July	August	September
2002	−0.85	−0.59	−1.84	−1.88	−0.77
2003	−1.14	−0.88	−1.62	−2.29	0.13
2005	−1.50	0.14	−0.79	−1.26	−2.23
2004	−1.41	0.72	−1.83	−1.58	−2.23

ble-heat flux changes its sign, the lake releases heat, and the total heat losses at the lake surface increase, as does the temperature gradient inside the skin.

A comparison between the results of control experiments without regard for the cool skin and the results of experiments with the Fairall parameterization of the cool skin incorporated into the LAKE model made it possible to estimate the influence that the presence of cool skin has on the heat balance B (formula (6.1)) at the surface of the body of water.

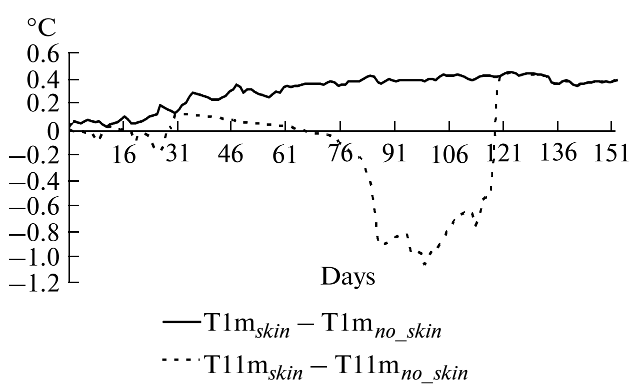

Fig. 3. Monthly mean temperature differences between the numerical experiment with allowance for the cool skin and the control experiment at depths of 1 and 11 m over the period of May–September 2003. The data presented in [18] are used as the atmospheric forcing.

The values of the heat balance B over the period from May to September for the experiments including the cool skin and without regard for the cool skin are presented in Table 6.

Negative values of the heat balance in this table indicate that, in the period from May to September, the heat flux is directed from the atmosphere into the water body and the water masses of the lake are heated. In the case, when the cool skin is taken into account, the water body receives approximately 2.5 GJ/m^2 more over the period of the experiment than without regard for the cool skin, which must lead to the additional heating of water body.

Table 7 contains the monthly mean differences between the heat balances at the surface of Lake Sparkling obtained in the experiments with allowance for the cool skin and in the control experiments. It is seen that this difference mainly takes negative values, which indicates that, in the first case, the heat flux from the atmosphere into the body of water is larger than in the second case and vice versa. It can be seen from Table 6 that the influence that the cool skin has on the heat balance is at its highest in the second half of the warm period, i.e., in August and September, and at its lowest in June. In some months, the difference $B_{skin} - B_{no\_skin}$ was positive. Such situations can be explained by the fact that, as is shown above, the cool skin leads, on the whole, to the heating of the water body, and, consequently, the surface temperature of the water body with the cool skin can, at a certain moment, exceed the surface temperature of the water body without the cool skin.

A comparison of the vertical temperature profiles obtained in the control experiments and in the experiments with allowance for the cool skin revealed the influence that the cool skin has on the thermal regime of Lake Sparkling. The daily mean differences between the water temperatures in the experiments with allowance for the cool skin and in the control experiment are presented in Fig. 3 for the depths 1 and 11 m over the period May–September 2003.

It is seen from Fig. 3 that the presence of the cool skin leads to the gradual additional heating of the water body at a depth of 1 m. By the middle of June, additional heating at a depth of 1 m attains 0.4°C and doesn't change very much to the end of the experiments. This behavior agrees with our suggestions that the cool skin leads to the additional heating of a water body.

As for the influence that the skin has on the thermal regime at a depth of 11 m, the pattern observed here is different. The main feature is the water temperature decrease in the experiment with allowance for the cool skin compared with the control experiment in July–August. Then, in August, the water-temperature difference between the experiments abruptly changes its sign and these differences at depths of 11 and 1 m become equal to each other. These features can be explained in the following way. The presence of the cool skin leads to the additional heating of upper layers of the water body, thereby making its stratification more stable. Therefore, the mechanism of turbulent heat transfer supplies a smaller amount of heat to the underlying layers, and the temperature at the depth 11 m decreases in the experiment with allowance for the cool skin as opposed to with the control experiment. At the end of the summer, the lake begins to cool from the surface and convection starts to develop, which drops the lower boundary of the mixed layer below 11 m. Thus, the water temperature levels out between the depths 1 and 11 m and a water body with the cool skin will, at a depth of 11 m, also be more heated than a body of water without the cool skin. A similar pattern was obtained for other years as well.

8. CONCLUSIONS

Several parameterizations of the cool skin were incorporated into the one-dimensional LAKE model of a water body: Fairall parameterization; Saunders parameterization; and simplified parameterization, where the skin thickness is specified by a constant. It can be inferred from the results of experiments that the LAKE model incorporating cold-skin parameterization successfully reproduces cold-skin characteristics, namely, the difference between the temperature at the surface of the cold-skin and the water temperature at a certain depth, $\Delta T_{skin} = T_{skin} - T_{bulk}$. The results of numerical experiments are within the variability of the results of in situ experiments presented in the literature [4–7]. When the Fairall and Saunders parameterizations were used in the model, the inverse dependence of the quantity ΔT_{skin} on the wind speed in the near-water layer, which is observed under natural conditions, was successfully reproduced.

Based on the numerical experiments with the LAKE model incorporating cold-skin parameterization on short time intervals (on the order of several days) performed in the coastal zone of the Black Sea and in the polynya of the Arctic Ocean, it has been shown that the presence of the cool skin decreases the heat losses of a water body. The influence that the cool skin has on the heat balance at the water-basin surface was expressed in the decrease (averaged over the time of experiments) in the heat flux from the ocean into the atmosphere by 3.5–4.5 W/m^2 for the Black Sea and by 10–19 W/m^2 for the Arctic. A decrease in the turbulent heat fluxes amounted, on average, to no more than 10% of their absolute values. With the inclusion of the cool skin, the flux of outgoing long wave radiation decreased by 1–2 W/m^2. The influence that cool skin has on the heat-balance components was of a systematic character, which suggested that, on longer time intervals, the effect of cold-skin presence will accumulate and lead to substantial changes in the thermal regime of a water body.

Experiments on cool skin reproduction on time intervals that are several months long for Lake Sparkling [18] showed that, at this time scale, the cool skin decreases, on average (from May to September), the heat losses of the body of water. With the inclusion of the cool skin, the heat balance at the reservoir surface decreased over the period from May to September by about 2.5 GJ/m^2 for each year from 2002 through 2005. The largest influence of the cold film on the heat balance took place in August–September, i.e. close to fall season when the total heat flux from temperate lakes into the atmosphere increases compared to summertime. The presence of the cool skin led to the heating of upper water layers in the lake by about 0.4°C, which, in turn, resulted in the formation of a more stable stratification in the lake. The formation of such stratification decreased the temperature of the water layers underlying the mixed layer; in some years, the water temperature at a depth of 11 m decreased at least by 1°C. Our results suggest that including the cool skin will lead to the additional heating of the mixed layer of a water body by the quantity ΔT_{skin}, mean for the period under consideration, and this heating supposedly will take place on different time scales.

The results of numerical experiments showed that the presence of the cool skin can change the thermal regime of a water body and its stratification due to changes in the heat balance at the surface. This fact can be taken into account when modeling many processes inside a body of water and at its surface, such as gas and heat exchange. It has been shown that the cold-skin effect, being accumulated, most significantly reveals itself on long time intervals. In connection with this, it should be noted that, according to the existing estimates [21], a systematic error of ±5 W/m^2 in the vertical heat flux at the ocean–atmosphere interface produces an uncertainty of about 0.4×10^{15} W in the interlatitudinal heat flux in the ocean (i.e., nearly 100% of the flux itself). Therefore, including the cool skin can be very important in modeling the general circulation of the atmosphere and ocean.

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