ISSN 0001-4370, Oceanology, 2009, Vol. 49, No. 5, pp. 595–606. © Pleiades Publishing, Inc., 2009.
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MARINE PHYSICS

Modeling and Experimental Research of Turbulent Jet Propagation in the Stratified Environment of Coastal Water Areas

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Received June 20, 2008

Abstract—The results of model calculations and experimental research of turbulent jet propagation in a stratified environment with reference to the Sand Island wastewater outfall (Hawaii) are considered. The jet's emergence and initial dilution were estimated on the basis of model calculations and experimental data of the stratified environment characteristics in 2003–2004. The reason for the appearance of the bidirectional quasi-isopycnic structure in the waste and ocean water mixing area was clarified, and an analysis of the *TS* index was carried out. The jet's features as calculated from the model and obtained from measurements with hydrophysical and hydrooptical instrumentation were found to closely correspond. The effects of the tides and hydrophysical conditions on the waste water's turbulent jet characteristics (the jet's floating-up depth level) have been revealed. The outcomes of the study corroborate the efficiency of the model as a tool for research of deep outfall turbulent jet propagation in the stratified environment of coastal water areas.

DOI: 10.1134/S0001437009050014

INTRODUCTION

As is well known, the coastal aquatic areas of seas and oceans are exposed to strong anthropogenic influence, among which polluted waste waters belong to the most harmful contaminants [1, 2, 9, 10]. The deep-sea waste water sources substantially affect the aquatic environment due to a broad spectrum of inherent processes and phenomena [1, 2, 4, 8, 11].

In [4], the author has fully considered a mathematical model describing the propagation of turbulent jets of waste waters, as well as the techniques for performing the numerical calculations for simulation of the jet floating up from the operational waste water discharge facility at Sand Island (Hawaii). In this Pacific Ocean region, the complex study of the anthropogenic impact of the deep-sea waste water discharge facility upon the ecosystem of the coastal area of Mamala Bay was conducted in 2002–2004 in the framework of an international project. In the course of this research, different space sensors were used for monitoring the aquatic area of interest along with sea-truth measurements of the hydrophysical, biological, chemical, and hydrooptical characteristics of the environment [1, 3, 5–7, 12–15, 17, 18, 21]. The sea-truth outcomes served as input data for the model calculations and for comparison with the results of the mathematical simulation. Based on the model calculations fulfilled, [4] reports the estimates of the depth level of the floating up and the initial dilution of the turbulent jets under the stratification conditions occurring in Mamala Bay from September 1 to 6, 2002. The comparison of the model's estimates of the features of the waste water turbulent jets with the experimental data revealed their excellent correspondence, which provides evidence of the ability of the mathematical model to adequately describe the propagation mechanisms of the deep-sea wastes [4].

A large body of information has been obtained as a result of the complex research accomplished in August–September of 2003–2004 aimed at the anthropogenic impact upon the Mamala Bay ecosystem caused by the deep-sea waste discharge from Sand Island [3, 5–7, 12, 14, 15, 21]. Combining this information with the modeling results makes it possible to undertake the detailed and deeper analytical treatment of the features of the waste water propagation in this area depending on the changes in the hydrophysical and meteorological conditions. The present paper describes the model's estimates of the parameters of the waste water turbulent jets that were discharged into Mamala Bay in August–September of 2003–2004 under diverse hydrological conditions. In addition, the model's output data were compared with the hydrophysical and hydrooptical observations, which allowed us to verify the proposed mathematical model.

SPECIFIC FEATURES OF THE PROPAGATION MODEL OF THE TURBULENT JET FLOATING UP

A mathematical model intended for estimating the depth level and dilution of the floating up of waste waters in a stratified medium [4] has been used to study the propagation features of turbulent jets of contaminated waters discharged into Mamala Bay. A distinguishing feature of our model is in the following. The jet propagation is described with a system of seven ordinary differential nonlinear equations that characterize the balance of the horizontal and vertical components of the momentum, the heat consumption, the salinity, and the jet coordinates with the system being supplemented with the equation of the state of the sea water. These equations have been obtained by integrating the equations of the motion, continuity, and heat and salt balance under the assumption of scaling of the distributions of the velocity, temperature and salinity in the cross section of the jet [4].

When deriving the equations, we considered a turbulent jet that was injected at the depth z into the aquatic medium at angle of Θ_0 to the sea line in the xz plain. The medium was assumed to be incompressible and quiescent, and its density $\rho_a(z)$ was depth dependent with $d\rho_a/dz < 0$, which means the stable stratification of the medium. It was supposed that the jet density $\rho(z)$ at the depth z is lower than the medium's density so that the jet tends to float up. The following designations were used: s is the coordinate along the jet axis, r is the radial coordinate, $u(s)$ and $\rho(s)$ are the jet's axial velocity and density, $\rho_0 = \rho_a(0)$ is the reference density, $b = b(s)$ is the characteristic half-width of the jet, and $\lambda = 1.16$ is a constant. The equation system looked as follows [4]:

$$\frac{d}{ds}(ub^2) = 2\alpha ub, \quad (1)$$

$$\frac{d}{ds}(u^2b^2\cos\Theta) = 0, \quad (2)$$

$$\frac{d}{ds}(u^2b^2\sin\Theta) = 2g\lambda^2b^2\frac{\rho_a - \rho_0}{\rho_0}, \quad (3)$$

$$\frac{d}{ds}[ub^2(T_a - T)] = \frac{1+\lambda^2}{\lambda^2}b^2u\frac{dS_a}{ds}, \quad (4)$$

$$\frac{d}{ds}[ub^2(S_a - S)] = \frac{1+\lambda^2}{\lambda^2}b^2u\frac{dS_a}{ds}, \quad (5)$$

$$\frac{dx}{ds} = \cos\Theta, \quad (6)$$

$$\frac{dz}{ds} = \sin\Theta, \quad (7)$$

$$\rho = \rho(T, S), \quad (8)$$

where $T_a(s)$ and $S_a(s)$ are the temperature and salinity of the medium, $T(s)$ and $S(s)$ are the temperature and salinity of the jet, and $\alpha = 0.057$ is the entrainment coefficient.

The jet floats up since it originates from a fresh water discharge enriched with different admixtures and has an initial density lower than that of the surrounding sea water [2, 4]. The floating up of the jet occurs due to the Archimedean force during the active period of the jet's propagation [2, 4]. The floating up terminates towards the end of the active period, and the subsequent propagation of the jet occurs approximately at one and the same depth level. The jet exhibits only relaxation oscillations relative to the depth reached at the close of the active period. The turbulent diffusion and currents typical of the coastal zone [2, 4] determine the further propagation of the jet. The use of this model makes possible the calculation of the resulting depth and the thickness of the jet propagation layer (the Ozmidov scale [11]) in the stratified medium, the initial dilution, and other features. A detailed description of the model is given in [4].

The mathematical model of the turbulent jet propagation in the stratified medium is implemented as a computer program. It was used to compute the characteristics of the floating up of the jet under the conditions that occurred in Mamala Bay in August–September from 2002 to 2004. The site of the deep-sea discharge facility in Mamala Bay is shown in Fig. 1a. When performing the model calculations, the following specifications of the Sand Island facility were used [16]: the mean total discharge rate was $Q = 4.64$ m^3/s, the mean rate of the discharge from a single diffuser orifice was $Q_0 = 0.0163$ m^3/s, the velocity of the jet outflowing from the diffuser orifices was $U_0 = 3$ m/s, the depth level of the diffuser site was $H = 70$ m, and the temperature of the discharged waters was $T_C = 25$–27.5°C. It was supposed that fresh water discharge took place.

The data of the hydrophysical measurements [5, 14, 15, 21] were used to understand the stratification of the aquatic medium. It is worth noting that there are strong tidal currents that substantially influence the diverse hydrophysical processes, including the propagation of the turbulent jets of the discharged waste water [3, 5, 13, 19, 20].

THE OUTCOME OF THE MODELING BASED ON THE MEASURED HYDROPHYSICAL PARAMETERS

In the performing the numeric calculations, advantage was taken of the vertical density profiles found from the temperature and salinity measurements at four anchored thermistor stations (thermistor chains) in Mamala Bay. Being designated Ca, Cb, Cc, and Cd, they were positioned as shown in Fig. 1a [5, 12, 14]. Stations Ca, Cb, and Cc were occupied along the 70 m isobath. In the field experiments of 2003, the measurements at station Ca, which was close to the diffuser, were conducted from August 27 until September 22 in

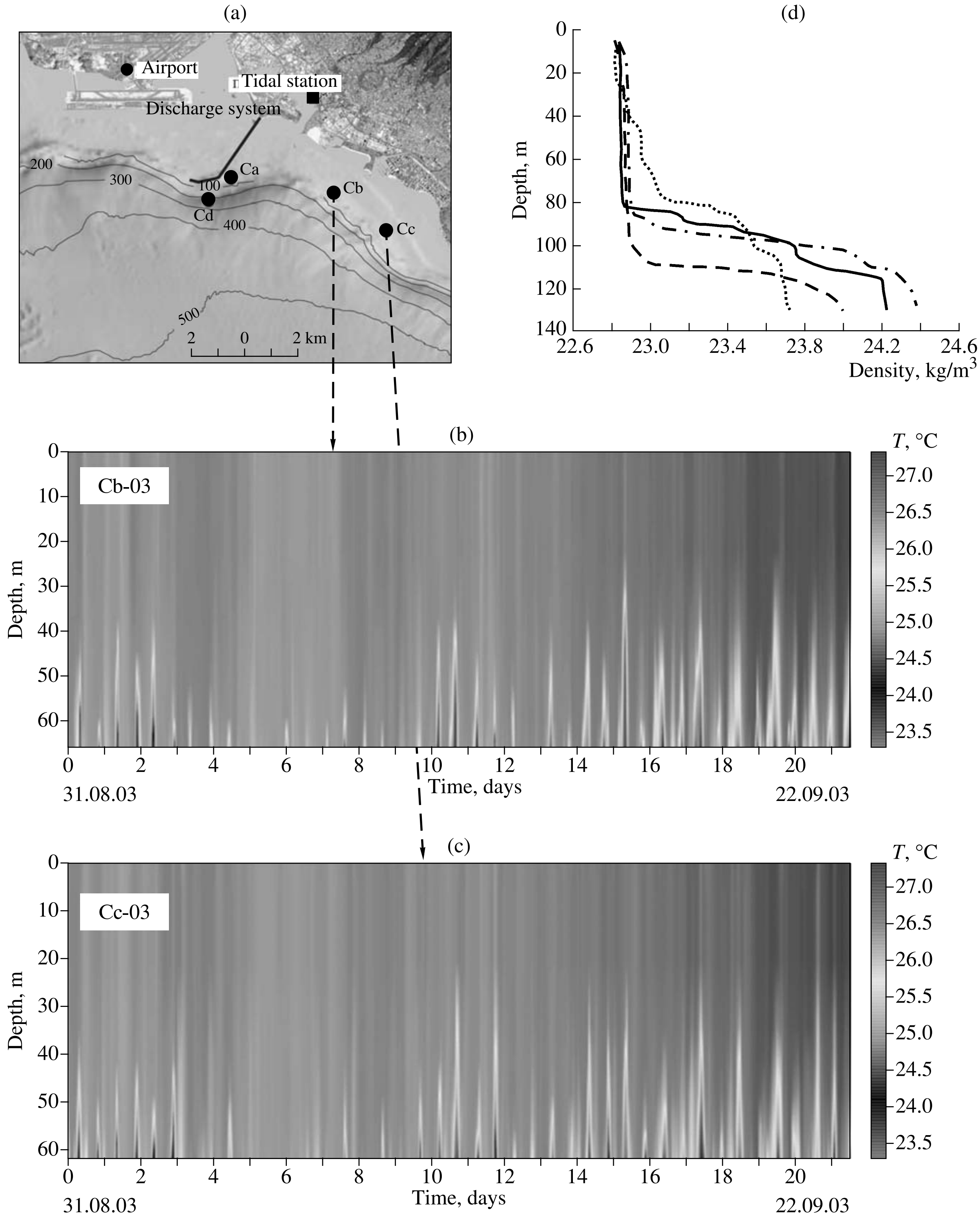

Fig. 1. Position of anchored thermistor stations in Mamala Bay (a); distribution of the sea water temperature from the data at station Cb measured from Aug. 31 to Sept. 22, 2003 (b); the same at station Cc (c); typical vertical density profiles in the Bay in September 2003 obtained from CTD measurements south of station Cd (d).

the depth range of 3.5–45.5 m at a sampling rate of 5 min. The local time is given throughout this paper. The measurements at stations Cb and Cc, which were spaced 3 and 6 km east of the diffuser, were conducted from August 31 to September 22, 2003, at depths of 20–66 m at a sampling rate of 2 min with the data being extrapolated down to 70 m.

There was more than 170 m of water at station Cd, which was located 1 km south of the diffuser. There, the measurements were performed from August 23 until September 7, 2004. The sensors were at depth levels from 17 to 68 m. In 2004, the measurements at station Ca lasted from August 14 to September 7 within the depth range of 20–80 m. The sampling rate equaled 30 s at all the stations, including stations Ca and Cd, during the field experiments of 2004 [6, 14].

The data acquired with the thermistor chains at stations Ca and Cd, which were anchored close to the diffuser (Fig. 1a), along with data of the ship borne microstructure and CTD probes [6, 12, 14, 15, 21], were used in the calculations of the turbulent jet's propagation parameters during the experimenting in 2004. As an example, Fig. 1b and 1c show the depth dependence of the temperature in Mamala Bay according to the measurements at stations Cb (b) and Cc (c) from August 31 to September 22, 2003. As follows from the long-period water temperature measurements at stations Ca, Cb, and Cc, the temperature regime of Mamala Bay in September 2003 considerably differed from the temperature conditions in September 2002, which were distinguished by substantial temperature changes in the depth and by strong stratification [4, 6]. The water temperature changed insignificantly around 26 ± 0.5°C most of the time in the surface ocean layers of 0–60 m at stations Cb and Cc (Figs. 1b and 1c) and in the surface ocean layers of 0–50 m at station Ca. The whole water thickness at these depths occurred in the upper well mixed quasi-homogeneous layer. For most of the measurement period, the pycnocline depth exceeded 80 m, which is evident from the CTD data obtained south of station Cd (Fig. 1d), so it was below the diffuser depth [6]. Hence, the pycnocline in the vicinity of the diffuser, being weak and deeper than the latter, could not be an obstacle in the floating up of the turbulent jet of waste water (Fig. 1d). Therefore, the water stratification above the diffuser was substantially weakened in 2003: as a rule, the temperature range was narrower than 0.5°C. Only a short-term increase in the temperature range occurred due to the internal semidiurnal tide (Figs. 1b and 1c) [6].

The vertical density distribution above the diffuser is needed to calculate the floating up and the initial dilution of the jet. The latter is determined by the ratio of the jet discharge rate at the depth of the jet floating to the discharge at the diffuser depth. Usually, the jet features are calculated from the profiles of the temperature and salinity. Star-Oddi CTD sensors [14, 17] for measuring the sea water temperature and the salinity were used at the thermistor stations. However, it was revealed that their electric conductivity data were wrong in 2003. In this connection, we took advantage of the temperature and electric conductivity profiles measured in Mamala Bay with the microstructure (MSS) and CTD probes [5, 12–15, 17, 21]. Figures 2a, 2b, and 2c demonstrate the temperature differences T[0 m] – T[70 m] between the upper and lower water layers (a), the initial dilution (b), and the floating depth (c) for the conditions from August 31 to September 20, 2003, corresponding to the location of station Ca. As follows from the model's calculations, the jet of the discharged waters frequently happen to reach the ocean's surface (Fig. 2c) with the initial dilution greater than >1000 (Fig. 2b). After September 14, 2003, the temperature range in the layer of 0–70 increased (Fig. 2a) and the outcropping of the jet became less frequent (Fig. 3c).

Figures 2d–2e display the changes in the ocean level (d), detailed plots of the temperature range between the upper and lower depths of the measurements (e), and the floating-up depth of the jet (f) for the time period of September 1–3, 2003 (the enlarged fragments of Figs. 2a and 2c) under the conditions corresponding to the site of station Ca. The analytical treatment of the data in these illustrations makes it possible to establish the time dependence between the ocean level variations caused by the tides and the features of the jet propagation. As follows from the plots in Figs. 2d–2e, the upwelling of cold waters from deeper layers occurring during the flow phase of the tide results in a considerable increase in the temperature difference between the upper and lower layers, which reduces the amplitude of the jet's ascension. The temperature difference between the upper and lower water layers reduces during the ebb phase of the tide, which facilitates the penetration of the discharged waters into the shallower subsurface layers.

These estimates provide evidence of the strong influence of the tidal currents on the patterns of the jet propagation of the waters discharged into Mamala Bay. This is typical of the season of the measurements (August–September). The lower limit of the upper quasi-homogenous layer can occur much higher than the diffuser depth level during other seasons (in the spring, for instance); consequently, the tidal effect on the floating-up height becomes less pronounced.

Figure 3 displays the temperature distributions in August–September of 2004 found from the measurements at stations Ca (August 14–28, 2004; Fig. 3a) and Cd (August 23 to September 6, 2004; Fig. 3b). The transects were plotted for the upper ocean layer of 0–70 m above the diffuser. Based on the distributions in Figs. 3a and 3b, it was established that the strong temperature variability was caused by the internal waves with the major contribution of the tidal oscillations of the semidiurnal period. This particularity was revealed in [3, 6, 9] as well. Nearby station Ca, the amplitude of an internal tidal wave became large to the extent (Fig. 4a) that the upper quasi-homogeneous layer occupied the whole

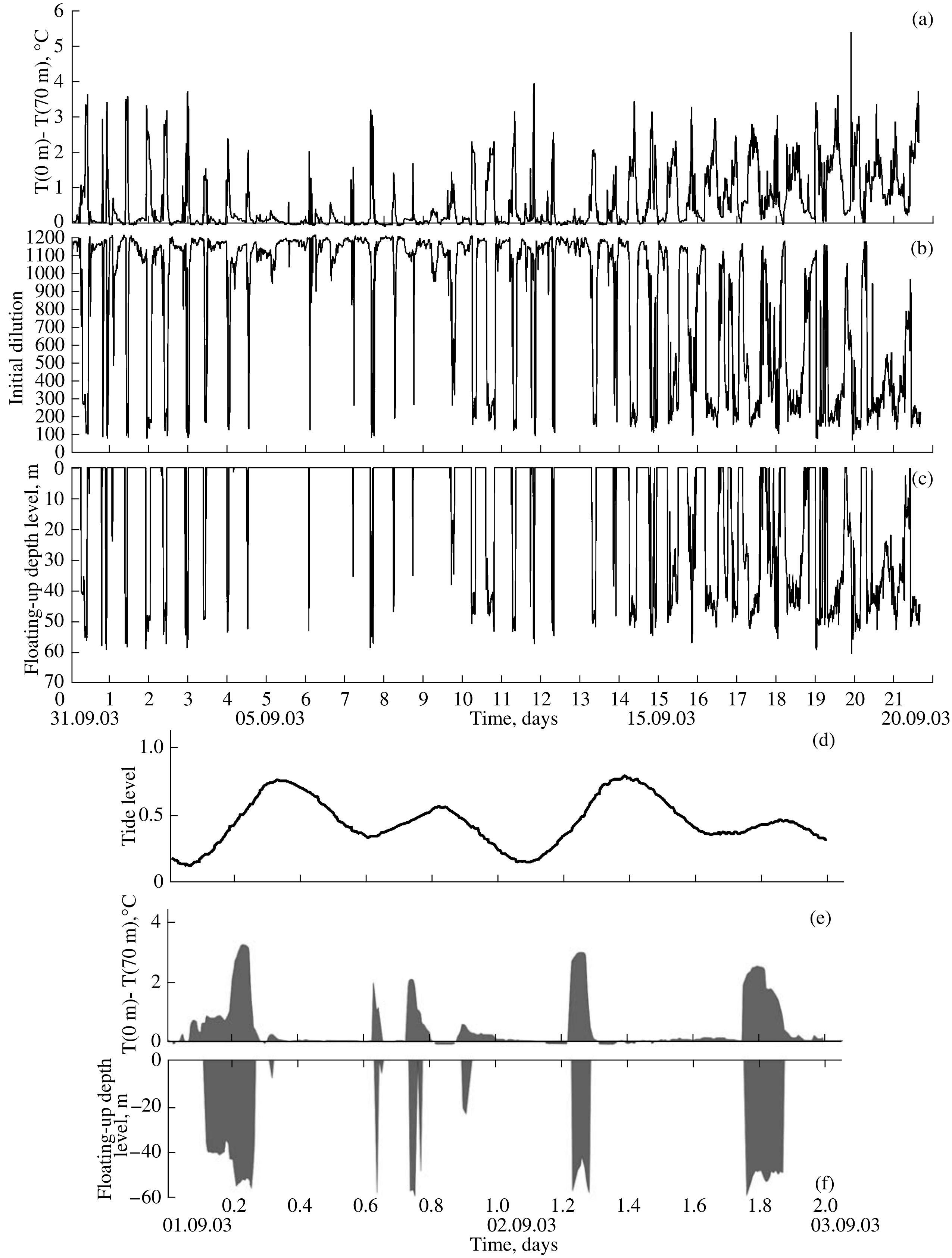

Fig. 2. Temporal variations of the temperature range between the upper (0 m) and lower (–70 m) water layer at station Ca from Aug. 31 to Sept. 20, 2003 (a); the same for the initial dilution of the jet (b); the same for the jet floating-up depth (c). Zoomed-in fragments of plots for the ocean level (d), for the temperature range (e), and for the jet floating-up depth level for Sept. 1–3, 2003 (f).

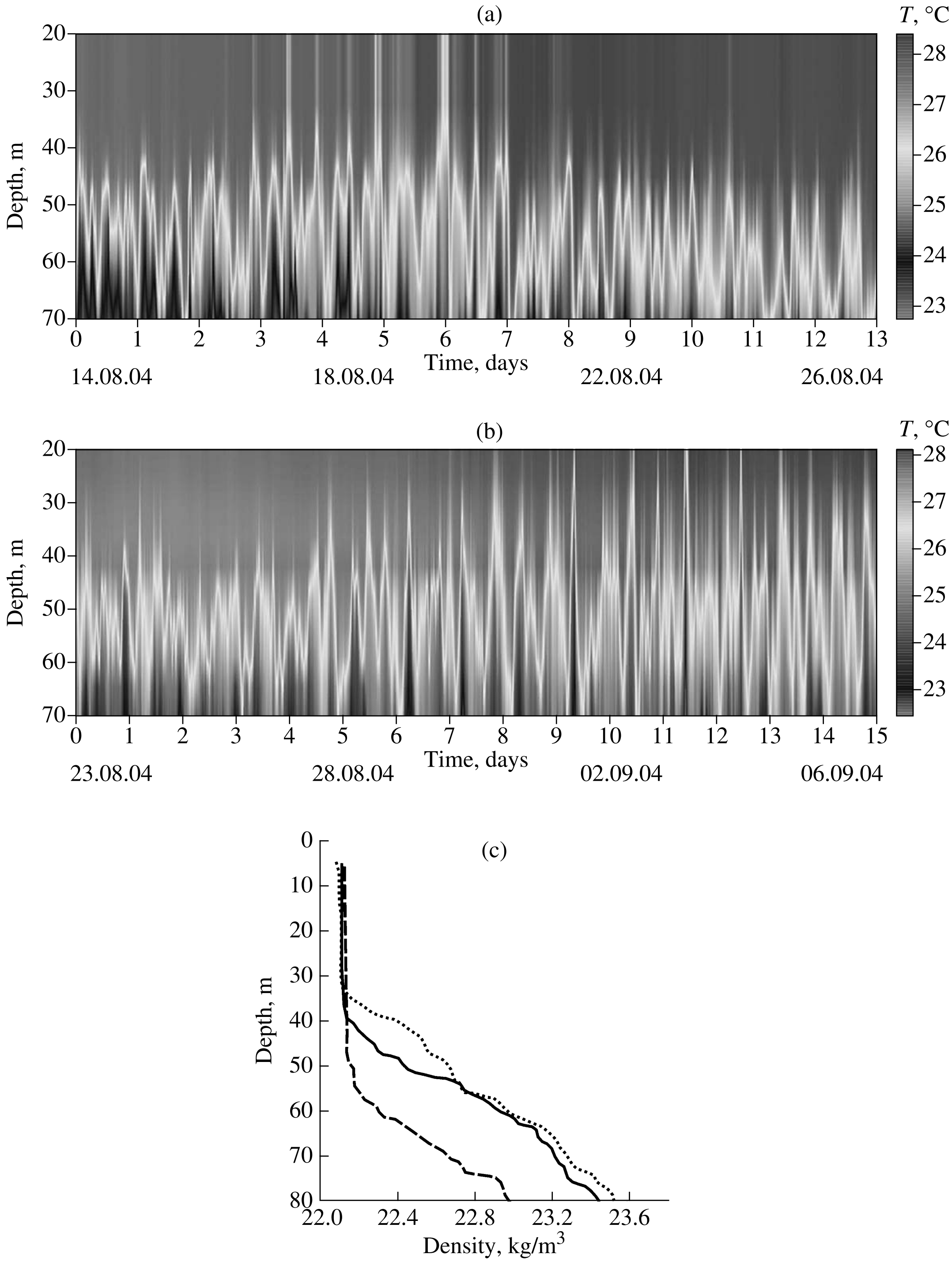

Fig. 3. Sea water temperature distributions in Mamala Bay from measurements in 2004 at station Ca from Aug. 14 to 26 (a) and station Cd from Aug. 23 to Sept. 6 (b) and density profiles close to the Cd station measured with a microstructure probe on Sept. 3, 2004 (c).

thickness down to 70 m in depth at the base of the wave. As station Cd was situated at a site where the water depth substantially exceeded (over 170 m) the depth in the vicinity of station Ca (~70 m), it is reasonable to suppose that the enhancement of the internal tide amplitude at station Ca relative to station Cd was due to the diminishing of the sea depth to a value insignificantly exceeding the thickness of the undisturbed upper quasi-homogenous layer. This effect is similar to the amplification of the surface waves running towards the shore at shoals.

The *TS*-diagram technique was used to determine the water salinity, because the electric conductivity measurements with the thermistor chains appeared to

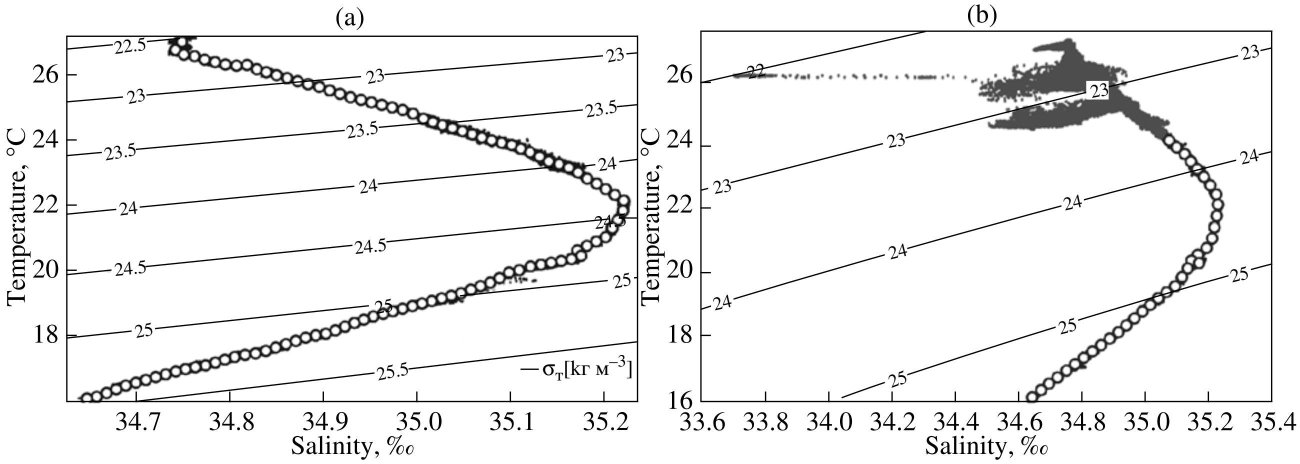

Fig. 4. *TS* diagrams from measurements with the MSS probe in the area of the background thermohaline stratification south of station Cc (light dots, (a)) and close to station Cd (dark dots, (b)) in the area of the ocean water mixing with the discharged fresh waters.

be too imperfect. In so doing, it was supposed that the variability of the thermohaline fields around the diffuser is described by a permanent *TS* diagram. If the *TS* diagram is known, it is possible to retrieve the salinity values using the temperature from the thermistor chain data and then to compute the vertical density profiles. This exemplifies the *TS* diagrams in Figs. 4a and 4b obtained from the microstructure probe measurements in Mamala Bay [14, 15, 21]. Figure 4a concerns station Cc (Fig. 1a), which is far from the diffuser and corresponds to the background thermohaline stratification undisturbed by the jet of the discharged waters. Figure 4b was designed from the microstructure data acquired in the vicinity of the diffuser (station Cd) and corresponds to the *TS* indexes of a mixture of the ocean water and the discharged fresh water. The light dots in the *TS* diagrams correspond to the background thermohaline stratification, while the dark dots designate the aforementioned mixture. Figure 4a demonstrates that the *TS* indexes of the disturbed waters are well fitted by a smooth curve.

Consequently, these curves allow us to retrieve the salinity estimate for each temperature value. The salinity calculations in the area of the thermistor stations were performed in the following way. Every temperature value Tc measured with the thermistor chain was compared with the temperature series from the microstructure probe T_i, where $i = 1, 2, 3,\ldots N$, in order to find i such that the condition $T_i \geq Tc \geq T_{i+1}$, $T_i > T_{i+1}$ holds. Next, the salinity value Sp was computed by the linear interpolation formula for the site of the thermistor chain:

$$Sp = S_i + (Tc - T_i)(S_{i+1} - S_i)/(T_{i+1} - T_i).$$

This technique was used to compute the salinity and the density of the water at the thermistor station sites.

The vertical profiles of the density measured with the microstructure probe on September 3, 2004, close to station Cd (Fig. 8a) are given as an example in Fig. 3c. Evidently, the pycnocline occurred at a depth of 30–50 m and prevented the penetration of the discharged water jet into the surface layer.

The outcomes of the model calculations of the initial dilution and the floating-up depth at stations Ca and Cd are shown in Figs. 5a and 5f. The time of the measurements at these stations since the starting moment is given on the *x*-axis in days. Under the stratification conditions characteristic of the site of station Ca (Fig. 1a), the jet remained mainly deep from August 14 until August 26, 2004 (Fig. 6b), excluding the shorter time periods when the diffuser occurred at the base of an internal tidal wave of large amplitude. At these moments, the temperature range became narrower than 1°C and the jet floated up for a short time. The enlarged fragments of Fig. 5b are shown in Figs. 5c and 5d. They represent the plots of the floating-up depth of the jet at station Ta during the short-period jet surfacing: (c) from 15:14 on Aug. 15 to 13:50 on Aug. 16; (d) from 23:50 on Aug. 20 to 21:02 on Aug. 21, 2004. It is notable that the stratification weakening during the flow phase of the tide was less pronounced and the jet surfacing did not occur at deep-water station Cd, where the tide amplitude was much smaller (Figs. 5e and 5f). Therefore, the jet was completely submerged and occurred at a depth of 25–55 m (Fig. 5f) from August 23 to September 6, 2004. In total, the pattern of the time dependence of the floating-up depth (Figs. 5b and 5f) and the initial dilution (Figs. 5a and 5e) in 2004 was the same as in September 2002 [4], which, apparently, is typical of the season from late summer to early fall in the ocean area under study.

The effect of the salinity stratification upon the height of the floating up and the initial dilution in the area of station Cd was calculated with consideration for the stratification presence and under the assumption of the salinity constancy ($S = 35‰$) within the depth range

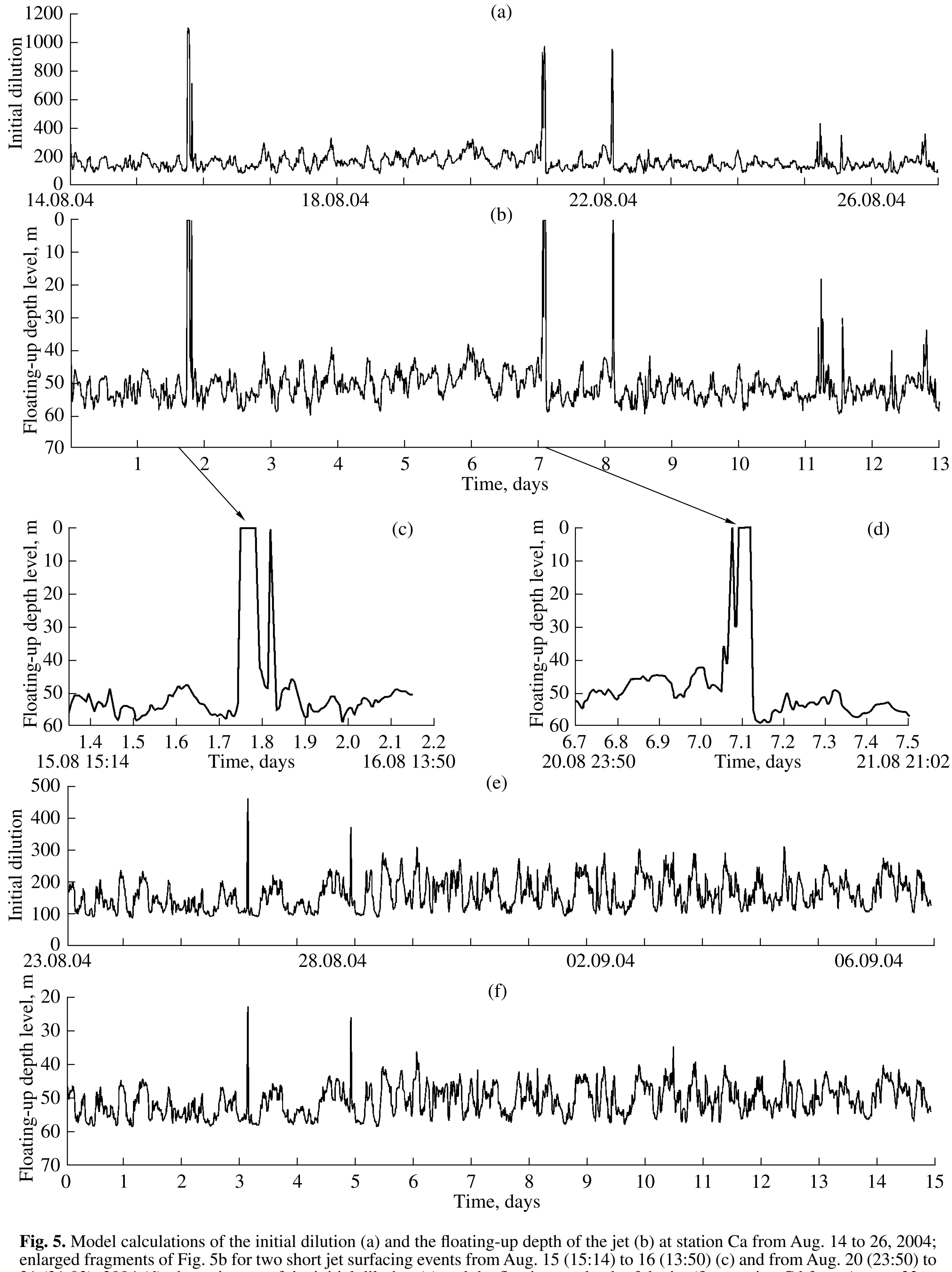

Fig. 5. Model calculations of the initial dilution (a) and the floating-up depth of the jet (b) at station Ca from Aug. 14 to 26, 2004; enlarged fragments of Fig. 5b for two short jet surfacing events from Aug. 15 (15:14) to 16 (13:50) (c) and from Aug. 20 (23:50) to 21 (21:02), 2004 (d); the estimates of the initial dilution (e) and the floating-up depth of the jet (f) at station Cd from August 23 to September 6, 2004. Hereinafter time is local.

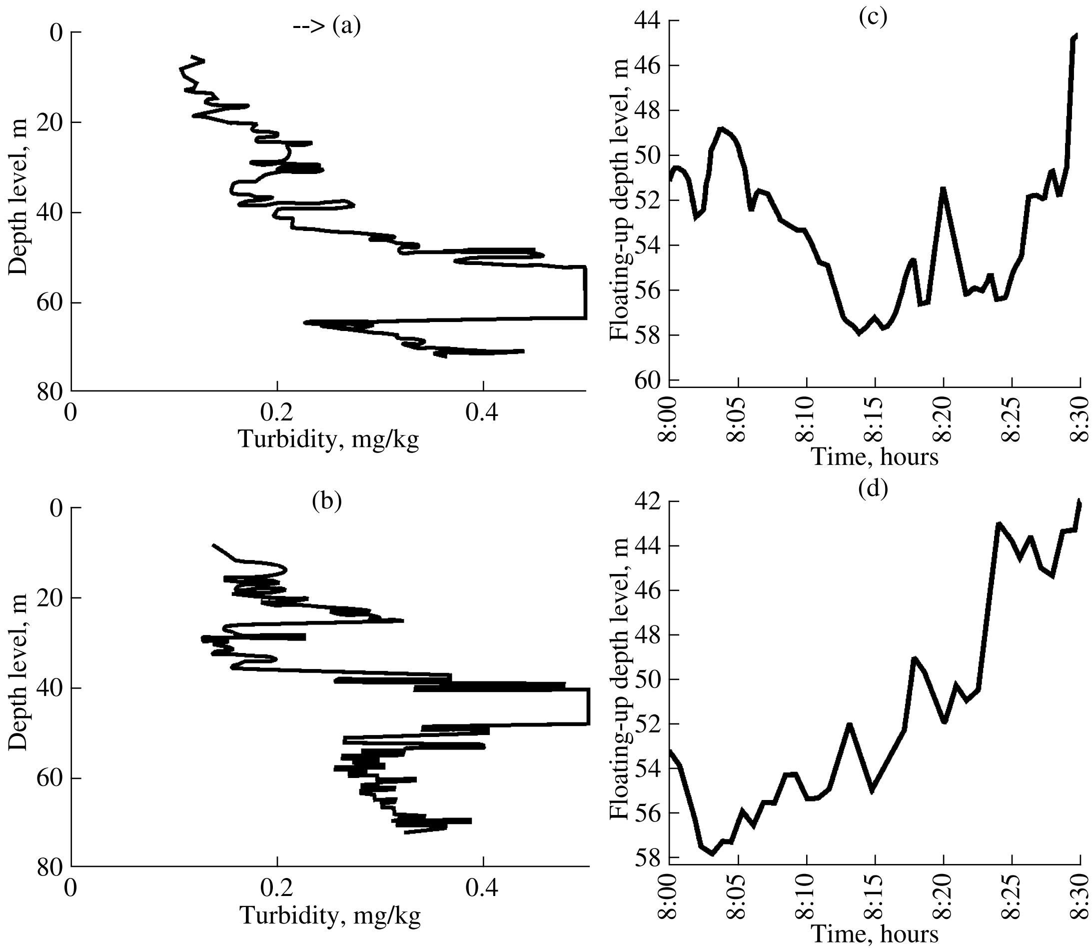

Fig. 6. Vertical profiles of the turbidity measured with the microstructure probe close to station Cd on Sept. 1 (08:17) (a) and on Sept. 2 (08:20), 2004 (b); model estimates of the floating-up depth level of the discharged water jet for the vicinity of station Cd on Sept. 1 (c) and on Sept. 2, 2004 (d) for the time period of 08:00–08:30.

of 0–70 m. It was found that the consideration of the salinity stratification reduces the height by ~2.2 m and decreases the dilution from 187 to 164.

ANALYTICAL TREATMENT OF THE *TS* INDEXES

In the calculations of the model's estimates of the jet's parameters in 2004, we computed the *TS* indexes on reaching the initial dilution, examined their distribution over the *TS* plain, and compared them with the field measurement results. The comparison of the calculated *TS* indexes with the measurement data revealed both correspondences and distinctions. The correspondence is in the fact that the *TS* indexes of the waste waters are biased towards lower salinity values—approximately by 0.4‰. The distinction consists in the following: the bias of the observation-based *TS* indexes is rather evenly distributed over the range of 0–0.4‰, while the bias of the computed indexes occupies the range of 0.1–0.5‰. The reason is that the computed *TS* indexes correspond to the jet axis, where they are the most distinct of the background undisturbed values, and to the moment of the initial dilution, when the jet has just floated up, while the *TS* indexes from the observations relate to the arbitrary distances from the jet axis and the "age" of the waste waters and can exceed the floating-up time (the emerging water has enough time to be isopycnically mixed with the surrounding waters). Another distinction consists in the fact that the observed *TS* indexes make up two quasi-isopycnic tongues, while the distributions of the computed *TS* indexes do not exhibit such a structure. Supposedly, the bidirectional isopycnic pattern of the *TS* indexes of the waste waters can be caused by the inconstancy of the ocean depth along the diffuser. Another probable reason is the insufficient statistical representativeness of the microstructure probe measurements in the immediate vicinity of the diffuser.

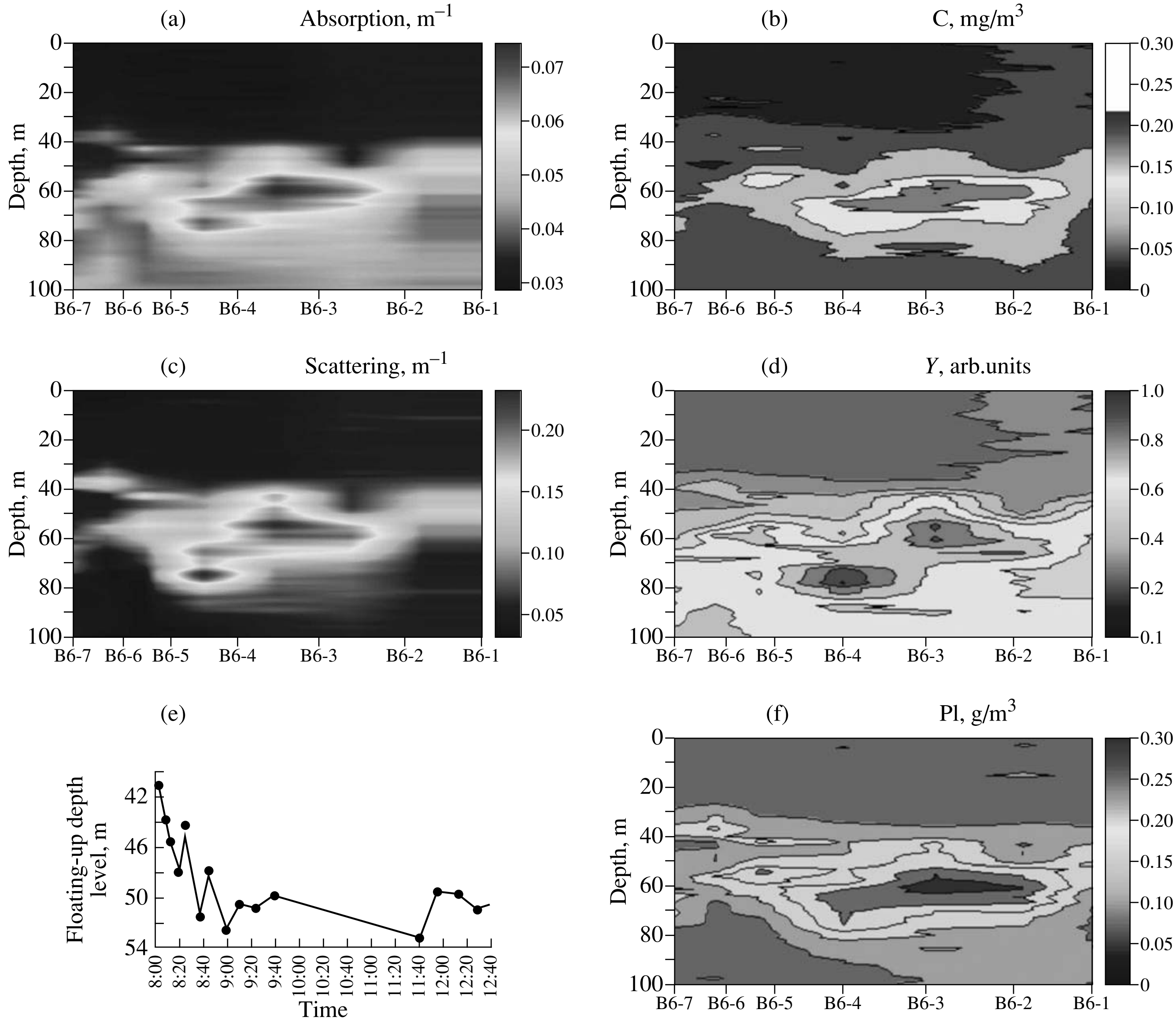

Fig. 7. Distributions of the coefficients of absorption (a) and scattering (c) measured with the AC-9 probe on Sept. 9, 2004 nearby the diffuser at B6-1 to B6-7 and the concentrations of chlorophyll (b), dissolved organic matter (d), and large particles (f) derived from the optical data; model estimates of the jet's floating-up depth level (e) on Sept. 3, 2004 during the 08:00–12:40 period. The quantity on the x-axes of plots 7a–7d and 7f is proportional to the distance from station B6-1 to station B6-7.

VERIFICATION OF THE MATHEMATICAL MODEL

The adequacy of our model for assessing the parameters of the turbulent jet was evaluated by the comparison of the calculation results with the experimental data. As stated above, the complex experiments in Mamala Bay near Sand Island were conducted using measurements with anchored station instrumentation along with towed and profiling microstructure probes and hydrooptical and hydrobiological sensors [1, 5–7, 12–15, 17, 8, 21]. The outcomes of these measurements were used to obtain the parameters of the jet propagation: the depth level of the floating up, the direction and speed of the propagation, and the concentration of the contaminants at different depths and distances from the diffuser.

Examples of the vertical profiles of the sea water turbidity recorded with the microstructure probe near station Cd on September 1 (a) and September 2 (b), 2004, from 08:00 to 08:30 are presented in Figs. 6a and 6b. These profiles show that the emerging jet of waste water, which is indicated by the higher turbidity, occurred in a layer 15–20 m thick at a depth of 40–60 m with mean depth level being 53 m. The modeling and calculation results for the same dates and time periods in Figs. 6c and 6d indicate that the jet floated up to the

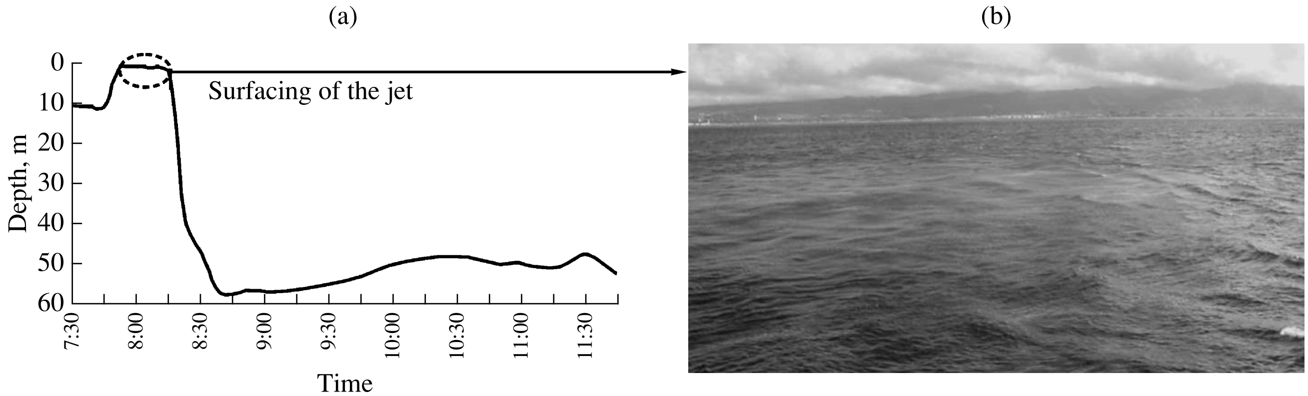

Fig. 8. Time dependence of the jet's floating-up depth level computed for the time interval from 07:30 to 11:45 on August 12, 2004, from measurements of the medium's stratification with the MSS probe, CTD sensors, and thermistor station Ca (a); still picture of the anomalous patch in the diffuser's vicinity taken on August 12, 2004, at approximately 08:00 (b).

42–58 m depth level, which agrees well with the in situ measurements (Figs. 6a and 6b).

In 2004, the light absorption and attenuation coefficients were measured with an AC-9 probe at nine wavelengths within the spectral range of 412–715 nm [5, 12], and these data were used to calculate the content of chlorophyll, the dissolved organic matter, and the small and large suspended particles in the water [5]. The measured quantities and the computed concentrations of the admixtures made it possible to determine the position of the water body contaminated from the deep-sea discharge facility, as was described in detail in [5].

Figures 7a–7f display the distributions of the coefficients of the absorption (a) and scattering (b) measured with the AC-9 probe on September 3, 2004, in transect B6-7–B6-1 near the diffuser. In addition, these same figures show the distributions of the chlorophyll concentration (b), the dissolved organic matter (d), and the large particles (f) computed from the above coefficients using the Haltrin–Kopelevich model [5]. The results for the time period from 11:45 to 12:17 and the sites most close to the diffuser have been selected to compare the model estimates of the jet propagation with the optical features of the aquatic medium. The optical data indicated the occurrence of the discharged water at a depth 50–55 m, which is close to the 50–53 m level found from the modeling (Fig. 7e).

A surface anomaly related to the floating up of the discharged waters was observed near the diffuser in 2004. A still picture of the anomaly taken on August 12, 2004 at 08:00 is given in Fig. 8b. Figure 8a shows the outcomes of the model calculations for the same day and time period from 07:30 to 11:45. The model indicated the surfacing of the jet from 07:50 to 08:15, which is in perfect agreement with the occurrence time of the anomaly. Similar events took place during the experiments of 2002 [4].

The good correspondence of the model's estimates of the propagation characteristics of the discharged water jets with the spatial patterns of the results of the hydrophysical and hydrooptical measurements corroborates the idea of the adequacy of the description of the turbulent jet propagation mechanism in the coastal aquatic areas based on our mathematical model.

CONCLUSIONS

The calculations of the features of the deep-sea discharge from Sand Island into Mamala Bay (Hawaii) were performed with the help of the mathematical model describing the turbulent jet propagation in a stratified medium. Based on the measured stratification characteristics, the model's estimates of the temporal variability of the floating-up depth and the initial dilution of the jet were obtained for the August–September season of 2003 and 2004. It has been shown that the stratification of Mamala Bay during this season is subjected to considerable oscillations due to the tidal currents and the internal tidal waves, which agrees well with the outcomes of other studies [3, 6, 13, 20]. It was established that the vertical tide-induced oscillations of the thermocline happen to be so significant that the discharged waters are able to reach the surface layer of the ocean even with the summer season's stable stratification.

As follows from the results of our study, in the course of the experiments in 2003, the upper quasi-homogeneous layer extended down to depths of 50–70 m and substantially weakened water stratification prevailed above the diffuser, which facilitated the frequent surfacing of the waste water jet. In 2004, stable stratification was typical of Mamala Bay and, respectively, the jet was submerged most of the time, excluding the short time periods when substantially weakened water stratification occurred above the diffuser because of high amplitude internal waves of tidal origin.

The comparison of the computed and measured *TS* indexes revealed their substantial distinction, which was pronounced in the uniqueness of the bidirectional quasi-isopycnal structure of the measured *TS* indexes in the zone of mixing of the discharged fresh waters with the ocean water. This structure supposedly occurs due to the lengthwise inclination of the discharge facility's diffuser, so that the inconstancy of the diffuser's depth exerts a stronger influence on the jet than the variations of the discharge regime.

We compared the model's computation results with the features of the admixture's jet propagation found from the field measurements with the help of the hydrophysical (CTD and MSS probes) and hydrooptical (AC-9) submersible probes. The comparison provided evidence of the good agreement of the observations and modeling and, consequently, of the ability of the employed mathematical model to adequately describe the mechanism of the turbulent jet's propagation in the stratified medium. The results of the mathematical modeling of the propagation of the discharged water jet in the marine environment have demonstrated the efficiency of using the proposed model for understanding the impact of the submerged waste discharge upon the coastal aquatic area.

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