ISSN 1028-334X, Doklady Earth Sciences, 2006, Vol. 409A, No. 6, pp. 948–951. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V.A. Akulichev, V.V. Bezotvetnykh, A.V. Burenin, E.A. Voitenko, S.I. Kamenev, Yu.N. Morgunov, Yu.A. Polovinka, D.S. Strobykin, 2006, published in Doklady Akademii Nauk, 2006, Vol. 409, No. 4, pp. 543–546.

GEOPHYSICS

Thermometry of Oceanic Shelf Zones by Acoustic Methods

Academician of the RAS V. A. Akulichev, V. V. Bezotvetnykh, A. V. Burenin, E. A. Voitenko, S. I. Kamenev, Yu. N. Morgunov, Yu. A. Polovinka, and D. S. Strobykin

Received March 28, 2006

DOI: 10.1134/S1028334X06060262

In this paper, we present the results of experimental investigations of the regularities of formation and interaction between hydroacoustic and temperature fields in a shallow sea in the shelf zone of the Sea of Japan. These experiments demonstrate that remote acoustic methods can be used for measuring and monitoring the temperature fields. This line of research, especially in experimental verification and technical maintenance, is a new and promising field, because it is related to the solution of many urgent issues, such as the forecast of climate changes, introduction of ecologically balanced technologies of fishing, regulation and replenishment of bioresources, and so on.

Shelf zones of oceans and seas are key objects for studying physical processes influencing the climate, ecology, and efficiency of the protection of marine borders. At present, the fishery industry of Russia is considerably reoriented to fishing in costal regions. The infrastructure of mariculture farms is rapidly developing. The correct choice of location, depth, and time of day for fishing and breeding biological objects depends significantly on the knowledge of the structure and dynamics of water masses. The application of traditional oceanographic instruments for in situ measurements is not effective in this case, because the technical realization of establishing measuring instruments at different depths in the entire water column of shallow regions with intense fishery and strong currents is related to large expenditures and risks. The development of methods of acoustic thermometry by the temperature field reconstruction based on measured transit times of sound pulses along the beams connecting the sound source and receiver located on the seafloor becomes pressing.

A detailed description of a time inversion can be found in [1]. Briefly, the method is based on the assumption that, for small perturbations of sound velocity profile

$$\delta c(z) = c(z) - c_0(z) \ll c_0(z)$$

the time change $\Delta\tau_j$ of acoustic pulse propagation can be written in the following form:

$$\Delta\tau_j = \tau_j - \tau_j^0 = \int_{\Gamma_j} \frac{ds}{c(z)} - \int_{\Gamma_j} \frac{ds}{c_0(z)} \approx -\int_{\Gamma_j} \frac{\delta c(z)}{c_0^2(z)} ds, \quad (1)$$

where the integral is taken along unperturbed natural beams Γ_j. For the set of T time perturbations and discretization of the vertical sound velocity profile in water into L layers, one can relate the vector of delay $\boldsymbol{\Delta\tau} = [\Delta\tau_1, \Delta\tau_2, \ldots, \Delta\tau_T]$ with the vector of perturbations of sound velocity profile $\boldsymbol{\delta c} = [\delta c_1, \delta c_2, \ldots, \delta c_L]$.

Technical realization of the method can be based on the application of complex phase-manipulated signals for sounding the sea medium with further calculation of cross-correlation function of the received and emitted signals. If the frequency range and parameters of the signal are chosen correctly, it is possible to resolve individual arrivals of acoustic energy in time, which are directly related to the velocity of acoustic energy propagation along different trajectories and temperatures in the corresponding layers [2, 3].

In this paper, we present the results of experiments carried out in August–September of 2004 and 2005 at the acoustic-hydrophysical test area of the Pacific Institute of Oceanology in the Sea of Japan. We organized a stationary acoustic track here during this period. A wide-band acoustic emitter was set up at a distance of 400 m from the coast at a depth of 39 m, while the depth of the seafloor was 40 m. At each minute during the day, complex phase-manipulated signals were radiated in the form of M sequences of 511 symbols with the central frequency equal to 2500 Hz. The receiving hydrophone was deployed at 2 km from the emitter at a depth of 43 masf. A cross-correlation function between the received and emitted signals was calculated at the

Il'ichev Pacific Institute of Oceanology, Far East Division, Russian Academy of Sciences, ul. Baltiiskaya 43, Vladivostok, 690041 Russia; e-mail: kamenev@poi.dvo.ru

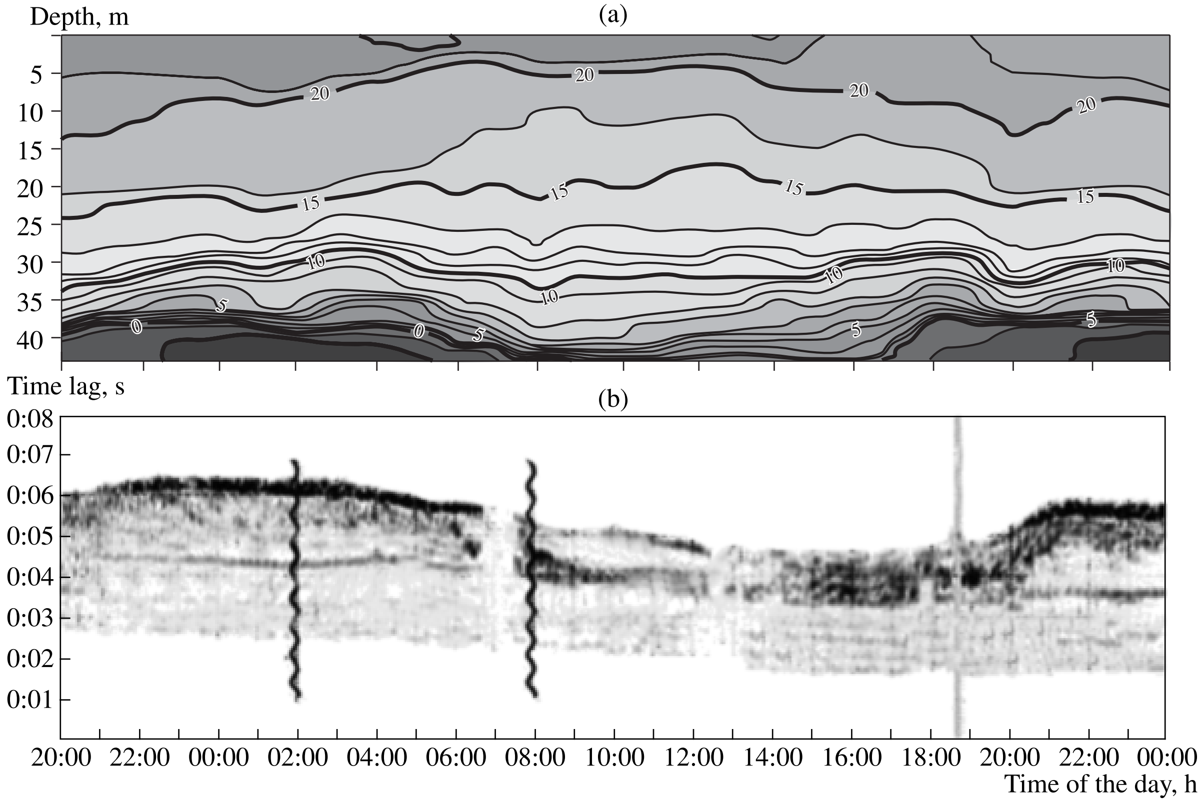

Fig. 1. (a) Dependence of temperature on time of day and depth and (b) variations in the pulse characteristic of waveguide in August 2005.

coastal laboratory on a real time basis. Thus, the variations in the travel time of the pulses along different trajectories were calculated. During the experiment, a yacht was anchored at the signal receiving point, where vertical profiles of temperature and salinity of seawater were measured each hour. The results of temperature measurements in August and September are shown in Fig. 1a and Fig. 2a, respectively. One can see that hydrological conditions in August and September were characterized by periodical semidiurnal variations in the temperature field with a two-mode character of internal tide propagation over the shelf; i.e., the warm water from the surface descends during the inflow of cold waters into the bottom layers.

Variations in the arrival time recorded in August and September over the acoustic track are shown in Fig. 1b and Fig. 2b, respectively. One can see that in both cases the best correlation is observed between the times of the latest arrivals of acoustic pulses with temperature variations in the bottom layer. During the inflow of cold bottom waters to the acoustic track between the emitter and receiver, the thermocline ascends to form a sound channel. Consequently, the main energy propagates along the beams with small angle of slide with minimal group velocities. During the ebb phase, when warm layers descend and the width of the bottom sound channel decreases, energy is redistributed into the upper part of the waveguide and the instruments record more powerful early arrivals formed by the beams with steep angles of slide and greater group velocities. In September, when the thermocline became thinner at 19:00–22:00 (Fig. 2a), we recorded a decrease in the arrival time of pulses with maximal amplitudes at 23:00–01:00, i.e., a time lag of 3 h (Fig. 2b). In August, when the bottom sound channel practically disappears at 08:00–17:00 (Fig. 1a), we recorded a complete redistribution of energy to earlier arrivals with the same 3-h lag (Fig. 1b). This can be caused by the following fact: the temperature was measured at the reception point; during that time, the acoustic track, which was oriented approximately perpendicular to the direction of the tidal front propagation, was filled maximally with either cold or warm water.

Diurnal dependences of the variations in early arrivals of acoustic energy formed by steep beams have a more complex character. However, even a qualitative analysis shows that they correlate with temperature variability in the upper layers of the waveguide. For example, the times of early arrivals decrease at 20:00–04:00 (Fig. 1b). The same is observed at 17:00–22:00 (Fig. 2b). This corresponds to the descent of warm waters to deeper layers during these time intervals (Figs. 1a, 2a). Numerical modeling using the beam acoustic methods was carried out for a more exact iden-

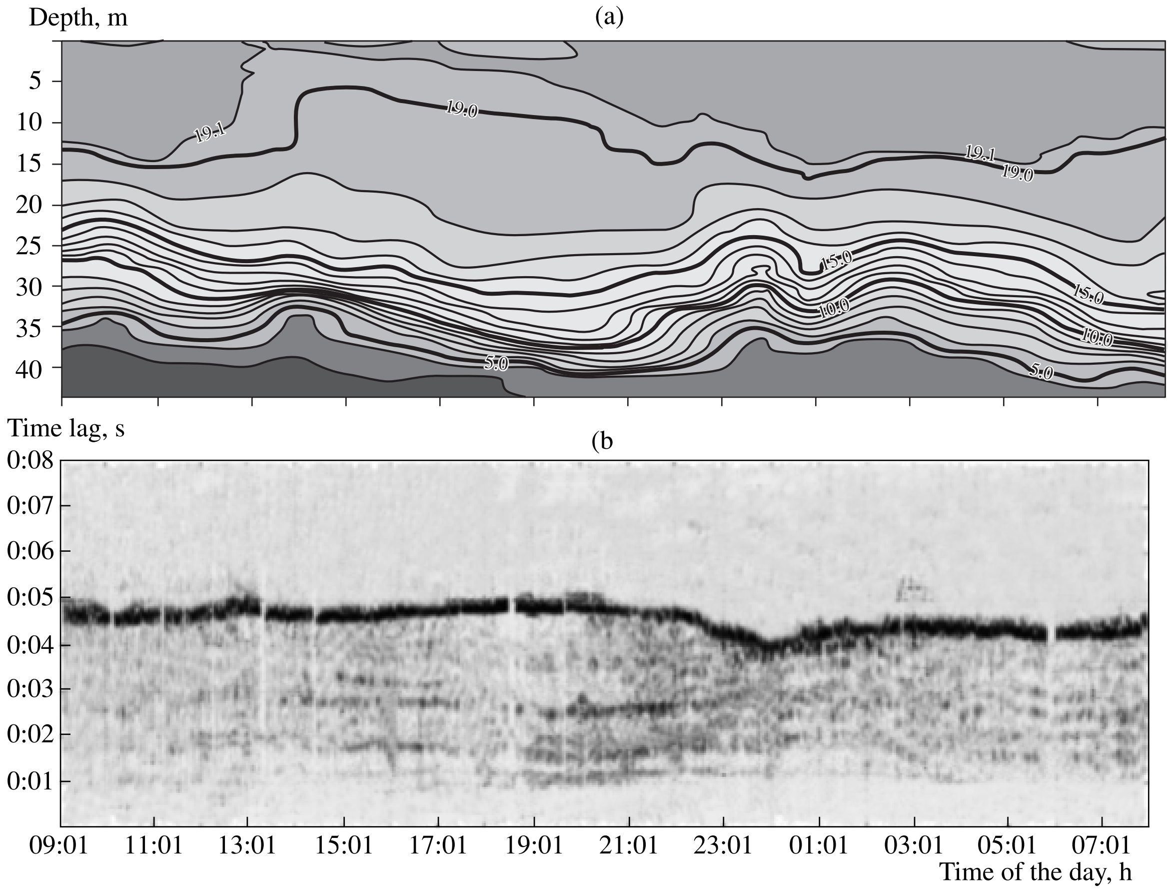

Fig. 2. (a) Dependence of temperature on time of day and depth and (b) variations in the pulse characteristic of waveguide in September 2004.

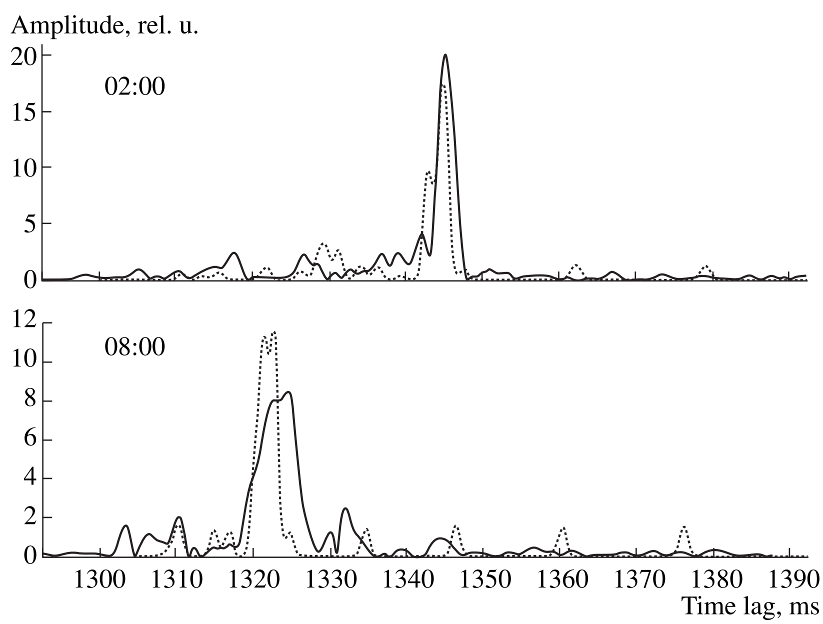

Fig. 3. Pulse characteristics of waveguide vs. time of day (02:00 and 08:00). Solid and dashed lines denote experiment and calculation, respectively.

tification of beam arrivals [4]. Figure 3 presents calculated and experimentally obtained pulse characteristics of the waveguide for two characteristic moments of tidal front propagation shown by winding lines in Fig. 1b. A rather strong correlation between the calculated and experimentally obtained amplitudes and transit times of sound pulses along different beam trajectories allows us to expect a successful solution to the problem of temperature field reconstruction. It is important to note that the transfer of information on the bottom temperature variation at the sound source point by variation of the emitted codes is not a difficult technical problem. Along with the possibility of satellite observation of surface temperature along the entire acoustic track, this will allow us to increase the accuracy of the solution of the inverse problem.

Thus, we have experimentally and theoretically revealed a direct relation between the transit times of acoustic pulses in different layers of the waveguide and temperatures at these depths. Therefore, we can state that the suggested method and equipment, which were experimentally tested in different hydrological conditions, have sufficient sensitivity for performing research and monitoring of the structure and dynamics of temperature fields in shallow basins. We have shown that low-cost and trawl-safe acoustic bottom systems can be effectively applied for thermometry of oceanic shelf zones.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research (project no. 04-05-65253).

REFERENCES

1. W. H. Munk and C. Wunsch, Deep-Sea Res. **26** (2A), 123 (1979).
2. V. A. Akulichev, V. V. Bezotvetnykh, S. I. Kamenev, et al., Dokl. Earth Sci. **381**, 990 (2001) [Dokl. Akad. Nauk **381**, 243 (2001)].
3. V. A. Akulichev, V. V. Bezotvetnykh, S. I. Kamenev, et al., Akust. Zh. **48** (1), 5 (2002).
4. M. B. Porterand and H. P. Bucker, J. Acoust. Soc. Am. **82**, 1349 (1987).