Секция D. Конденсированные состояния. БШФФ-2009. С. 338–340

УДК 556.556.3

ВЕРТИКАЛЬНАЯ СТРУКТУРА ТЕМПЕРАТУРНЫХ СПЕКТРОВ И ВНУТРЕННИЕ ВОЛНЫ В ЮЖНОМ БАЙКАЛЕ

Н.М. Буднев, С.В.Ловцов, И.А. Портянская, А.Э. Растегин, В.Ю. Рубцов

VERTICAL STRUCTURE OF TEMPERATURE SPECTRA, AND INTERNAL WAVES IN SOUTH BAIKAL

N.M. Budnev, S.V. Lovtsov, I.A. Portyanskaya, A.E. Rastegin, V.Yu. Rubtsov

Описаны результаты спектрального анализа температурных рядов на выделенных частотах, отвечающих волнам определенного типа в оз. Байкал. Структура спектров исследуется как функция глубины. По характерным периодам вычислен фурье-образ температуры как функция глубины и времени. В 2000 г. на глубинах 340 и 390 м амплитуда возросла в 1.6 раза по сравнению со значением на 288 м, что может указывать на наличие узла вертикальной моды волны. Ввиду относительно слабой стратификации состояние покоя близко к нейтрально устойчивому. Сходное возрастание имеет место для периодов 2 сут, 12 ч и 278 мин. Пиковое значение отвечает началу осенней гомотермии. При этом рост спектральной интенсивности прямо свидетельствует о вкладе внутренних волн. Обнаружена явная интенсификация возмущений вблизи дна, что указывает на существование в придонной области движений жидкости специфического вида.

Results of spectral analysis of temperature series are described. The analysis was made for typical frequencies related to some kinds of wave motions in lake Baikal. Structure of spectra is examined as function of depth. There are several typical periods of oscillations of the lake. The Fourier transform of temperature was estimated as function of depth and time. In 2000, amplitude for depths of 340 m and 390 m increased by factor of 1.6 in comparison with that for 288 m. This fact may be interpreted as manifestation of the node of vertical mode of wave propagation. Water stratification at these levels is weak; consequently, the quiescent state is close to the neutral stable one. Similar increasing is observed for periods of 2 days, 12 hours, 278 minutes. The maximum amplitude corresponds to beginning of the autumn homothermy. Under these conditions, an unexpected increase in amplitude indicates occurrence of internal waves. Moreover, intensification of excitations near the bottom is observed. This observation indicates water moving in the bottom area; this is not typical of the main water thickness.

In this paper, we describe results of spectral analysis of temperature series and their related conclusions. Examination was made for typical frequencies connected with certain kinds of internal waves in Lake Baikal. Observations are carried out at the place of the Baikal Neutrino Telescope location [1]. The Baikal Neutrino Telescope Project has provided new opportunities for continuous monitoring of water dynamics. For example, new insights into origins of deep-water renewal were gained [2]. The telescope is situated in South Baikal (104 030′ E, 51 045′ N) at the distance of 3.5 km from the coastline. Due to exceptional variety of possible oscillatory motions of distinct scales, separation of contribution of specific wave kind into total energy balance is very difficult. In the previous paper [3], we analyzed seasonal changes in total spectral density of temperature at several horizons. In this paper, dependence of spectrum structure on depth is investigated. In a certain sense, this allows us to complete general knowledge on energy exchange between different spatial-temporal scales motions.

One of perspective methods is to make spectral analysis with respect to the chosen periods concerning certain kinds of oscillatory motions. Wave motions of different types and spatial-temporal scales can be induced in natural reservoirs. Typical periods for Lake Baikal are 278, 140, 93 and 70 minutes for seiches, 12 hours for tidal oscillations, about 15 hours for inertial waves, and 2–5 days for meteorological excitations [4]. For all mentioned periods, the Fourier transform $T(z,t\,|\,\omega)$ of temperature is calculated as a function of time and depth (moment t is a center of sampling window of 25 days). The maximum of $T(z,t\,|\,\omega)$ for $\omega = \dfrac{2\pi}{120\ \text{hours}}$ for each of horizons in 2000 is shown on Fig. 1. It should be emphasized that amplitude for depths of 340 m and 390 m increased by factor of 1.6 in comparison with that for 288 m. This local minimum may be interpreted as manifestation of vertical eigenfunction node. The same increase was observed for periods 2 days, 12 hours, and 278 minutes. Due to relatively weak stratification, an unexpected growth of spectral intensity directly mentions on development of internal waves with corresponding periods. In addition, we call attention to the fact that considerable intensification of perturbations takes place in the bottom layer. It is important that such observation was made for all proceeded years. On the basis of such excitations existing one may conclude that motions of specific kind are regularly developed in the bottom layer. Thus, we have found another confirmation of the well-known fact.

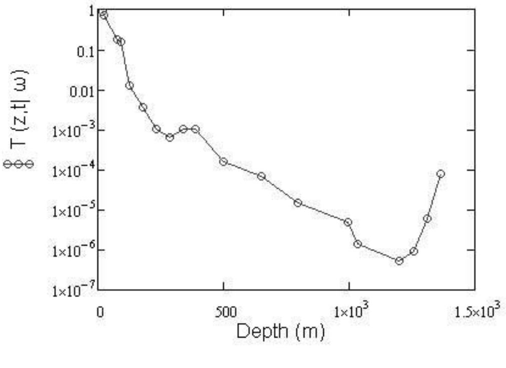

Fig. 1. Maximal values of $T(z,t\,|\,\omega)$ on the horizons of thermistor installation in 2000.

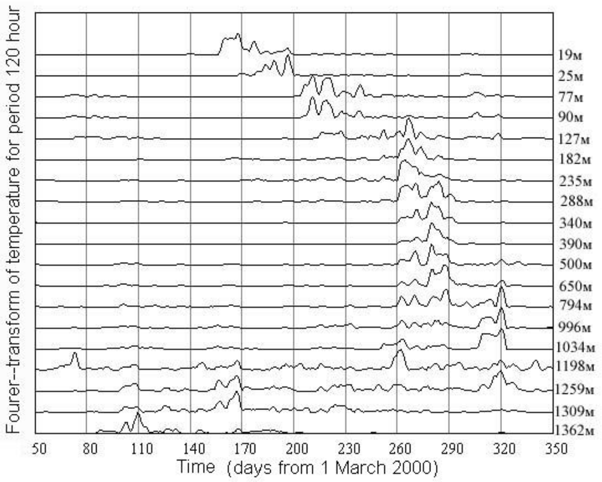

Fig. 2. Fourier transform of temperature series in 2000.

On Fig. 2, a the Fourier transform of temperature series versus time is shown at different levels for 2000. Each curve is normalized in such that its maximum is equal to one. After that, we run the line through this maximum. Using time intervals between peaks on curve levels and distance between levels, one can estimate speed of vertical energy propagation through water thickness. We obtain value of ~0.18 centimeters per minute. This is a typical value of energy propagation along the vertical for the site of data acquisition [2]. In the paper [5], results of processing the temperature data within the model with diffusivity and mass-transfer coefficients are presented. We may point out the following fact of some interest. When homothermy is forming, the lower boundary of mixing area displaces down with similar rapidity. Let us merely call attention to this point.

Investigation into spectral characteristics of internal waves requires detailed information about spatial-temporal changes in water velocity. However, direct measurements of velocity fluctuations are a very difficult experimental task. Nevertheless, temperature data can be used for the above purposes. Much of internal wave energy is usually pertinent to lower modes [6]. Let t_M denote maximal period of these oscillatory motions. Then fluctuations of temperature and velocity are approximately related by [6]

$$T' \approx t_M \nabla \overline{T}\, \vec{u}', \tag{1}$$

where T' is the temperature fluctuation, $\vec{u}'$ is the velocity fluctuation and $\overline{T}$ is the averaged temperature. The gradient of temperature is mainly defined by stratification in situ. Dependence of spectral density of T' is known for inertial-convective interval in the form [6]

$$E(k) \sim k^{-5/3}. \tag{2}$$

The correlation function of temperature is defined as

$$S(\tau \mid t\,0, z) = \frac{1}{\Delta t}\int_{t0}^{t0+\Delta t} T(t+\tau, z)\,T(t, z)\,dt, \tag{3}$$

where t0 is the first moment of sampling window. The Fourier transform $S(\omega \mid t0, z)$ of this function can de related to dependence (2) due to the approximation (1). Using the above reasons, we have compared a spectral picture with dependence

$$S(\omega \mid t\,0, z) \sim \omega^{-5/3}. \tag{4}$$

For the given point of time and depth, we fit calculated quantity $S(\omega \mid t0, z)$ by power function $\sim \omega^{\alpha\,(-5/3)}$ and estimate parameter α. The results for 2000 and 2004 are shown on Fig. 3. In the areas with estimated value of α close to one, the above power law may be regarded as adequate. In 2000, the stratification was clearly expressed. According to Fig. 3, *a*, points with α≈1 are especially observed in the presence of homothermies and also formation of autumn homothermy. This result was predictable from the following fact. Except for the periods close to homothermy, the evaluated value of vertical diffusivity was found as relatively small during almost the entire 2000 [5]. By contrast, the stratification was atypically weak in 2004. In comparison with Fig. 3, *a*, points with α≈1 are expanded into very large area on Fig. 3, *b*. We do not state that the lake thickness was occupied by free convection in 2004. We only point out that observed spectral picture indicates presence of intensive mixing processes during almost the entire year. In general, this interesting matter deserves more detailed study.

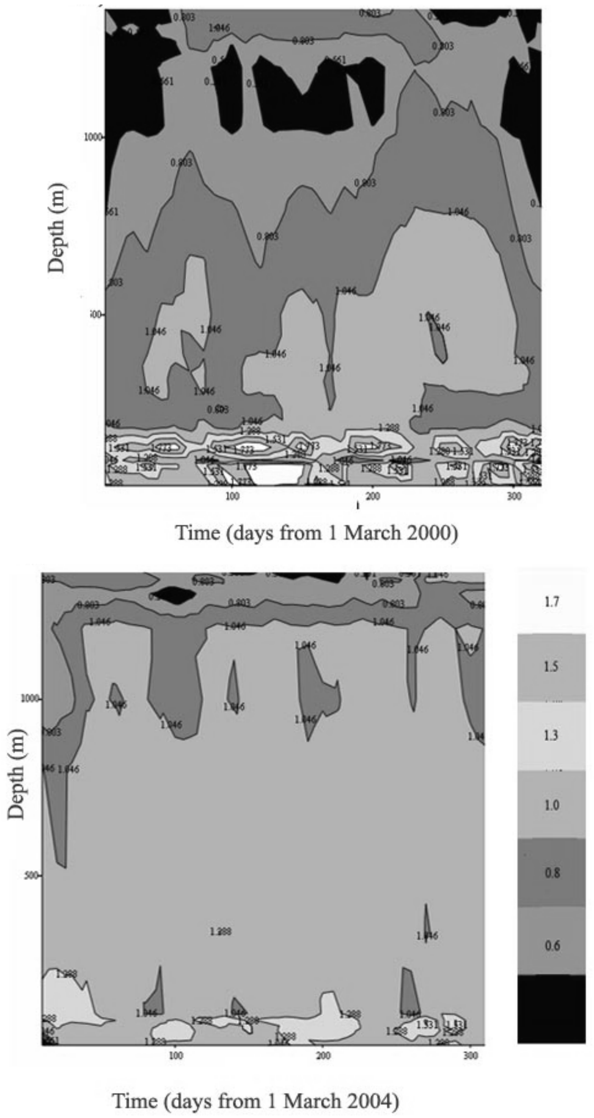

Fig. 3. The evaluated parameter α as a function of time and depth for 2000 and 2004. The case α=1 is pertinent to the power law (4).

Authors thank everybody from the «Baikal» collaboration for their help. This work was supported in a part by the Ministry of Education and Science of the Russian Federation (projects No. 2.2.1.1/1483, 2.1.1/1539, 02.740.11.0018). We acknowledge the financial support by the «Russian Foundation for Basic Research» (projects No. 05-05-97262, 05-02-16593, 06-02-31005, and 07-05-00948) and Research Educational Centre «Baikal» of the Irkutsk State University.

REFERENCES

1. Shimaraev M.N., Verbolov V.I., Granin N.G. Sherstyankin P.P. Physical Lymnology of Lake Baikal: a review // Baikal International Center for Ecological Research. Print N 2, Irkutsk; Okayama, 1994. 81 p.

2. Schmid M., Budnev N.M., Granin N.G., et al. Lake Baikal deepwater renewal mystery solved // Geophys. Res. Lett. 2008. V. 35. P. L09605.

3. Budnev N.M., et al. Temperature Spectra as Indices of Vertical Energy Transfer in the South Baikal // Selected papers. International conference «Fluxes and structures in fluids» (St-Peterburg, 2–5 July, 2007). Moscow, 2008. P. 35–40.

4. Ivanov-Rostovtsev A.G., Kolotilo L.G., Tarasyuk Yu.F., Sherstyankin P.P. Self organization and self regulation of natural systems (model, method and basics of D-SELF theory) / Ed. K.Ya. Kondrat'eva; Russian Geographical Society. Saint-Petersburg, 2001. P. 171–180 (in Russian).

5. Budnev N.M., et al. Simulation of temperature regime of Lake Baikal upper layers using experimental data of 2000–2001 // Selected papers. International conference "Fluxes and structures in fluids" (St-Peterburg, 2–5 July, 2007). Moscow, 2008. P. 214–219 (in Russian).

6. Monin A.S., Ozmidov R.V. Oceanic Turbulence. Leningrad: Gidrometeoizdat, 1981. 320 p. (in Russian).

Иркутский государственный университет, Иркутск