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GEOPHYSICS

Influence of Exogenous Factors on Deep Heat Flow

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In recent years, the Geological Institute, Russian Academy of Sciences, has carried out research chiefly in the West Arctic region (Svalbard and Franz Jozef Land). There have been four expeditions of the R/V *Academician Nikolai Strakhov* to this region since 2006. Measurements were made using a GEOS-M telemetric multichannel probe [1].

Most of the works were carried out in the areas of Knipovich Ridge and the western Svalbard Plate. During the expeditions, 66 new heat flow values were obtained and they have convincingly shown the relationship between the geothermal field and the locations of hydrocarbon fields [2].

In the 28th cruise of the R/V, the study area was the southwest Barents Sea. Heat flow measurements at the Fedynski swell, at a depth of no more than 300 m, have indicated the very intensive influence of exogenous factors on the deep heat flow. The influence of seasonal periodic oscillations of temperature at the sea floor due to insolation was identified, as well as that of high-debit near-bottom currents. This factor is especially noticeable in the southern part of Barents Sea, where the influence of the Norwegian–Kola branch of the Gulf Stream is detected. With respect to this, direct probing did not allow conditional estimates of deep background heat flow to be obtained, because it was problematic to separate the deep geothermal gradient from the background of intensive exogenous temperature anomalies (Fig. 1a).

To obtain the conditional values of heat flow measurements for water areas, areas of great depth (more than 500 m) and with no strong near-bottom currents, i.e., those where an isothermal near-bottom water layer is formed (Fig. 1b), are preferred for study. However, the predominant part of the shelf zones within the Barents and Kara seas, where these conditions are absent, remains promising for hydrocarbons. So, further geothermal studies in these areas are necessary. Geothermal studies help determine the depth of the catagenetic temperature interval (110–180°C), where organic matter transforms into hydrocarbons. In addition, all the gas and oil deposits are already explored in the Barents–Kara region coincide with the geothermal anomalies that can be considered as one of prospecting indicators. The influence of exogenous factors in studies of this kind should be taken into account using model corrections or by measurements at depths below the "neutral layer."

In practice, study of the geothermal regime of the shelf zone was based on analysis of experimental data collected in the contact zone between water and bottom sediments [3, 4]. To calculate the temperature correction at this boundary or the depth of the "neutral layer" (where the exogenous factor does not affect the results), we should have regular observations of the near-bottom temperature for several years. Since there is a developed hydrological network in the Russian part of the shelf zone (hydrological stations measure properties of water in different layers) [5], the basis for such a calculation is available.

The defect of the methods mentioned in the literature is that the input data for formulas (more precisely, the amplitude and oscillation period) are set from the statistical estimates, which imposes a certain error on the resulted model. Of course, this is not a good point, because the amplitude and oscillation period are the destination parameters. To eliminate these defect, the method of harmonic analysis is proposed.

In the expansion, the function is written in the form of a trigonometric series [6]:

$$T(t) = a_0 + 2\sum_{m=1}^{n-1}\left(a_m \cos\frac{m \cdot 2\pi t}{L} + b_m \sin\frac{m \cdot 2\pi t}{L}\right) + a_n \cos\frac{n \cdot 2\pi t}{L},$$

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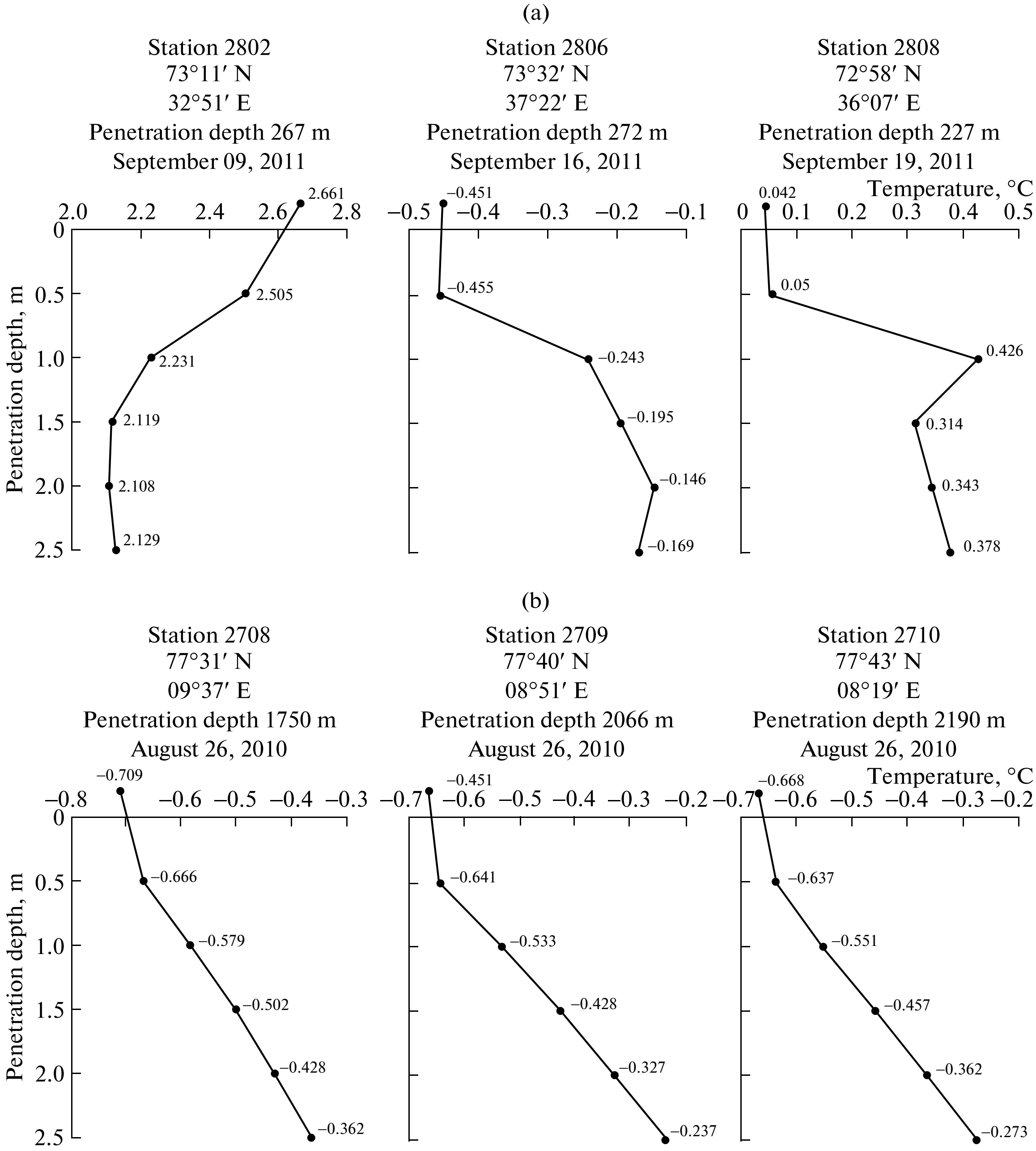

Fig. 1. Examples of ground thermograms obtained during the cruises of R/V *Akademic Nikolai Strakhov* in the West Arctic region: (a) 28th cruise, September 2011; (b) 27th cruise, August 2010.

where a_0 is an average temperature for time period L; $n = \frac{N}{2}$ is the quantity of harmonics (N is the quantity of measurements); m is the ordinal number of the harmonic; L is the time period during which observations were made; a_m and b_m are the sought constants.

In some cases, this expression can be written as follows:

$$T(t) = A_0 + 2\sum_{m=1}^{n-1} A_m \cos(\omega_m t + \varphi_m) + A_n \cos\omega_n t,$$

where $A_m = \sqrt{a_m^2 + b_m^2}$ is the amplitude of the mth harmonic at the sea bottom surface, $\varphi_m = \arctan\left(-\frac{b_m}{a_m}\right)$ is the phase of the mth harmonic, and $\omega_m = \frac{m2\pi}{L}$ is the frequency of the mth harmonic.

When harmonic oscillations at the sea bottom surface are obtained, we can estimate their attenuation in the ground:

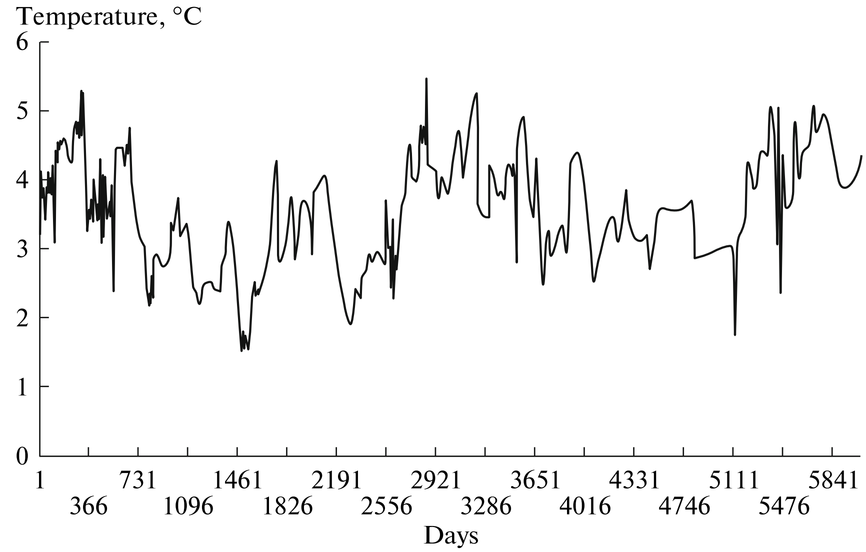

Fig. 2. Measurements of near-bottom temperature from February 1975 until May 1991.

$$T(z,t) = A_0 + 2\sum_{m=1}^{n-1} A_m e^{(-k_m z)}\cos(\omega_m t - k_m z + \varphi_m) + A_n e^{(-k_n z)}\cos(\omega_n t - k_n z),$$

where $k_m = \sqrt{\frac{\omega_m}{2\chi}}$ is the spatial frequency (χ is the thermal diffusivity).

To find the "neutral layer," it is sufficient to determine the maximal possible depth of influence for these oscillations. Therefore, let us find the depth where the sum of amplitudes of all harmonics is less than or equal to the set error δT:

$$A_\Sigma(z) = 2\sum_{m=1}^{m-1} A_m e^{(-k_m z)} + A_n e^{(-k_n z)}.$$

Thus, we must find the depth z_{neut} where $A_\Sigma(z_{neut}) \le \delta T$.

To implement this method in practice, we can use the data on the near-bottom water temperature from the digital atlas [5]. In most of the Barents Sea, an isothermal near-bottom water layer exists; its thickness is 4–8 m, depending on the sea depth. At a sea depth of more than 150 m, the near-bottom water temperature coincides with the bottom temperature at 0.03–0.04°C error; hence, we can use the data on the temperature regime of near-bottom water as the boundary conditions [6]. The mentioned digital atlas is a reference book on the regime and contains data on the climatic characteristics of the marine environment of the Barents Sea. Unfortunately, the measurements are presented only in the form of monthly averaged values. The full time series is unavailable; therefore, only intra-annual oscillations can be analyzed.

To exemplify, let us consider the time series of variations in near-bottom temperature in the shelf zone of the Barents Sea for a 17-year period (courtesy of L.M. Galerkin, Shirshov Institute of Oceanology, Russian Academy of Sciences). The measurements were implemented in a zone of 1° × 1° with the coordinates of the upper left and lower right ones being 71° E, 34° N and 72° E, 33° N, respectively. After a day-based averaging (with respect to the nonperiodic character of the measurements) and interpolation, the data series was obtained (Fig. 2). In total, 6100 temperature values resulted. For analysis using the fast Fourier transform, the first 4096 (2^{12}) values were used [7].

It is seen from the spectrum that the main harmonics are the oscillations with periods of 11.2 years, 3.7 years, and 1 year long (Fig. 3); the amplitudes are 0.652, 0.456, and 0.426°C, respectively. The obtained cycles agree well with the values given in the literature [8].

Analysis of the time series suggests that the neutral layer depth is 20.5 m (with the temperature conductivity of sediments being 2×10^{-7} m^2/s). At this depth, surface oscillations of the temperature will affect the deep temperature by less than 0.01°C. However, this is a great depth at which to perform heat flow measurements. At present, there are no probes that can perform measurements at such a depth. Hence, drilling of shallow boreholes is necessary, but this is much more laborious than probing.

In such a situation, we can use another approach, which is based on calculation of thermal wave propagation in the ground at the moment of measurement. It helps perform studies using conventional instruments, only additional expected error is introduced into the final result of deep thermal flow.

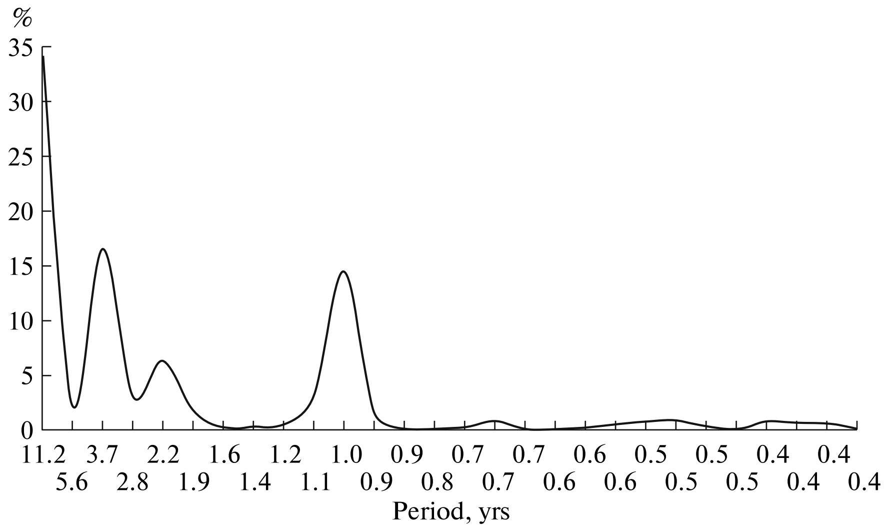

Fig. 3. Contribution (%) to the variable signal intensity (first 27 harmonics).

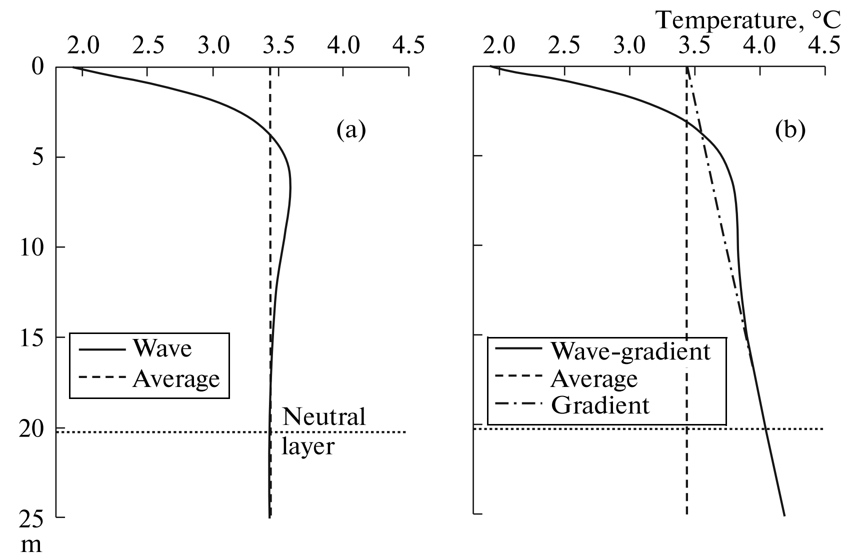

Fig. 4. Propagation of surface temperature wave in the ground (prediction for August 1, 2015): (a) without gradient; (b) with gradient.

For example, if the studies are planned to be implemented in the mentioned area of the Barents Sea in August 2015, an inverse Fourier transform should be done on the basis of the obtained spectrum, and the time series can be extrapolated to the desired date.

In our case, the initial point is February 13, 1975, so all the subsequent calculations have to be based on it, otherwise the initial phases of harmonics will change. To get the date of August 1, 2015, we must introduce $t = 14\,568$ days. The resulting temperature at 2 m depth is 3.060°C (Fig. 4a).

However, in the general case, the value of the temperature field in the ground $S(z, t)$ depends on the sum of two components, namely, the outer effect $T(z, t)$ and the deep thermal source $G(z)$:

$$S(z, t) = T(z, t) + G(z).$$

By the time moment t_i, for the sampling of 4096 temperature values in the Barents Sea (Fig. 2), we have

$$S(z) = \left[A_0 + 2\sum_{m=1}^{n-1} A_m e^{(-k_m z)} \cos(\omega_m t_i - k_m z + \varphi_m) + A_n e^{(-k_n z)} \cos(\omega_n t_i - k_n z)\right] + [g \cdot z],$$

where g is the temperature gradient (Fig. 4b).

As is seen from this formula, the exogenous effect on the temperature field does not depend on the depth of heat flow. However, against the background of high heat flow, an exogenous wave is less discernible, giving greater reliability of the estimate of deep heat flow under anomalous conditions, analogous to [1].

Thus, if temperature measurements on depth $S(z)$ are available for a point and regular temperature observations have been made on the surface $T(z = 0, t)$, the value of the geotemperature gradient can be calculated:

$$g = \frac{1}{z}\left(S(z) - \left[A_0 + 2\sum_{m=1}^{n-1} A_m e^{(-k_m z)} \cos(\omega_m t_i - k_m z + \varphi_m) + A_n e^{(-k_n z)} \cos(\omega_n t_i - k_n z)\right]\right).$$

In practice, the final result will obviously have some error: due to measurement error, due to approximation of the time series, and due to the probabilistic nature of any prediction. However, in the absence of valid (for example, borehole) measurements of unaffected deep heat flow, the proposed algorithm can give an estimated value.

Note that harmonic Fourier analysis is not a universal tool for studying the thermal conditions at the water–bottom boundary. This method is well developed and works well with stationary models, but frequency-time representation of a signal is better if the parameter changes nonperiodically. In this case, a possible effective approach is a wavelet transform [9]. However, if only the value of a neutral layer depth is needed, then the spectral characteristics obtained by the Fourier transform are sufficient.

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