Spatial-temporal analysis of temperature in Lake Shira based on long-term observations

Olga S. Volodko[1], Lidiya A. Kompaniets[1] and Lyudmila V. Gavrilova[2]

[1]*Institute of Computational Modeling SB RAS, Krasnoyarsk, Russia*
[2]*Siberian Federal University, Krasnoyarsk, Russia*

Abstract
Long-term in-situ measurements of temperature were conducted in lake Shira during 2013-2015. The principal component analysis of temperature time series allowed to identify period of generation and propagation of internal waves. The spectral analysis revealed the dominance of the oscillations with periods of 21.3, 10.6 and 5.3 h.

Keywords
In-situ measurements, internal waves, spectral analysis, isotherms.

1. Introduction

The dynamics of water currents are studied intensively in order to analyze the distribution of impurities and phytoplankton and, thus, to determine characteristics of water systems.

Lake Shira located in the Republic of Khakassia, Eastern Siberia, is an enclosed saline lake with only a small tributary of the Son River. In the period of summer stratification, the wind stress is a main factor induced the water currents.

The observations on many stratified lakes confirm that one of the most common wind reactions is the occurrence of internal waves [1], which determine the intensity of mixing in the coastal zone, and therefore biological processes and water quality in lake.

In present work, the periods of internal waves has been determined using spectral estimates of temperature of 2013–2015.

2. Long-term temperature measurements

In summer of 2013–2015 in lake Shira long-term temperature measurements were carried out at several stations of the lake, as shown in Figure 1. The temperature measurements were performed using thermal circuits. The temperature were measured with interval of 1–1.5 m and with accuracy of 0.5 °C in 2013–2014, and the accuracy of 0.1 °C in 2015.

The temperature data of 2013–2014 of four stations T2, T3, T4, T5 were analyzed from 03.07.2013 to 05.08.2013 and from 01.07.2014 to 21.07.2014. The data of 2015 were analyzed from

SDM-2021: All-Russian conference, August 24–27, 2021, Novosibirsk, Russia
osv@icm.krasn.ru (O. S. Volodko); lv.gavrilova@gmail.com (L. V. Gavrilova)

Figure 1: The stations of temperature measurements in 2013 (left), in 2014–2015 (right).

seven stations T1, T2, T4, T7, T8, T9, T10 with depth 15.7, 23.6, 24.4, 13.8, 17.5, 17 and 12.9 m correspondingly of two periods from 8.07.2015 to 11.07.2015 and from 01.07.2015 to 01.08.2015.

3. Spectral analysis

The spectral estimates of temperature were found using the method of averaged periodogram with Blackman – Harris window and the Welch's method [2]. In the last method signal is split up into eight overlapping segments and then averaged windowed using Blackman – Harris window. On the each segment the periodorgam is calculated by computing discrete Fourier transform

$$D_n = \frac{1}{N}\sum_{m=0}^{N-1} f_m W^{mn}, \quad n = 0, 1, 2, \ldots, N-1,$$

where $\{f_m, m = 0, 1, 2, \ldots, N-1\}$, $W = e^{-2\pi i/N}$ is discrete exponential functions. The discrete Fourier transformation is computes using fast Fourier transformation, that allows to obtain result in time of $O(N \log N)$.

In article [3] were presented analysis of temperature data in period from 01.07.2015 to 01.08.2015 using method of empirical orthogonal functions (principal component analyses). The analysis identified periods of generation and propagation of internal waves. During the time-period from 08.07.2015 to 11.07.2015 the internal waves were observed with period 7 and 9 hours (Figure 2). Therefore, these 4 days and the entire measurement time period from 01.07.2015 to 01.08.2015 were chosen for spectral analysis.

The spectral estimations in period from 08.07.2015 to 11.07.2015 were found for original data, in period from 01.07.2015 to 01.08.2015 the temperature data were pre-processed with decimation every 15 minutes (Table 1). The Figures 3–8 shows temperature spectrums.

The spectral analysis of temperature showed the frequencies longwave oscillations for period four days are include in frequencies longwave oscillations for period a month (see Table 1).

Table 1
The spectral estimations of temperature of 2015.

Frequency, 1/hr	Period, h	Spectral power density, W/(1/h)	Frequency, 1/h	Period, h	Spectral power density, W/(1/h)
Station T1			Station T2		
08.07.2015–11.07.2015					
0.04688	21.3	4.415	0.07031	14.2	0.00728
0.1172	8.5	0.2474	0.1172	8.5	0.004908
0.1875	5.3	0.08537	0.1875	5.3	0.002681
01.07.2015–01.08.2015					
0.04688	21.3	0.9873	0.03125	32	0.2594
0.0625	16	0.9592	0.0625	16	0.2738
0.09375	10.6	3.091	0.09375	10.6	0.2059
0.1172	8.5	2.891	0.125	8	0.1107
0.1953	5.1	1.396	0.1484	6.7	0.1829
			0.1953	5.1	0.07305
Station T4			Station T7		
08.07.2015–11.07.2015					
0.04688	21.3	0.04632	0.04688	21.3	0.04848
0.09375	10.6	0.002482	0.1172	8.5	0.003557
0.1875	5.3	0.0003167	0.1875	5.3	0.001335
01.07.2015–01.08.2015					
0.04688	21.3	0.1065	0.03125	21.3	6.179
0.0625	16	0.4059	0.08594	11.6	3.486
0.08594	11.6	0.2201	0.1094	9.1	0.5561
0.1016	9.8	0.2497	0.1328	7.5	0.1603
0.1484	6.7	0.1335	0.1484	6.7	0.2788
0.1797	5.5	0.04446	0.1797	5.5	0.1763
Station T8			Station T9		
08.07.2015–11.07.2015					
0.09375	10.6	0.0007315	0.07031	14.2	0.001293
0.1406	7.1	0.001111	0.1406	7.1	0.001111
			0.2109	4.7	0.001112
01.07.2015–01.08.2015					
0.07031	14.2	0.3639	0.02344	42.6	1.399
0.08594	11.6	0.814	0.03906	25.6	0.522
0.125	8	0.1068	0.0625	14.2	0.6069
0.1406	7.1	0.1728	0.08594	11.6	0.8786
0.1563	6.3	0.1129	0.1563	6.3	0.08016
0.1953	5.1	0.06089	0.2031	4.9	0.1576

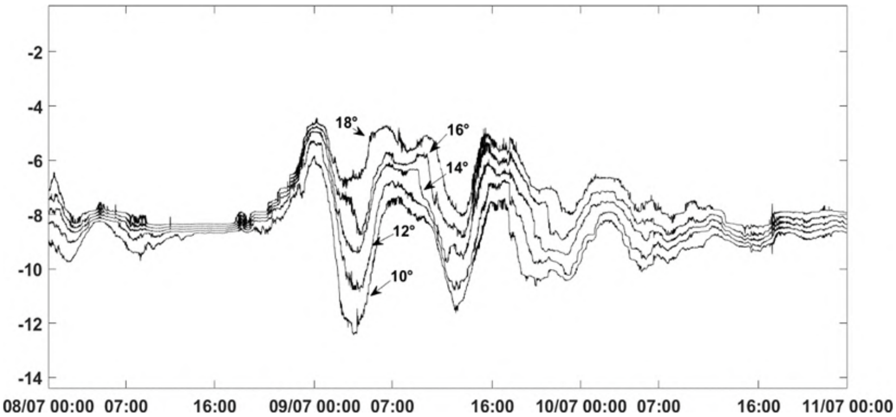

Figure 2: The isotherms in the station T1 of period from 08.07.15 to 11.07.2015, $T = 10$, 12, 14, 16, 18 °C.

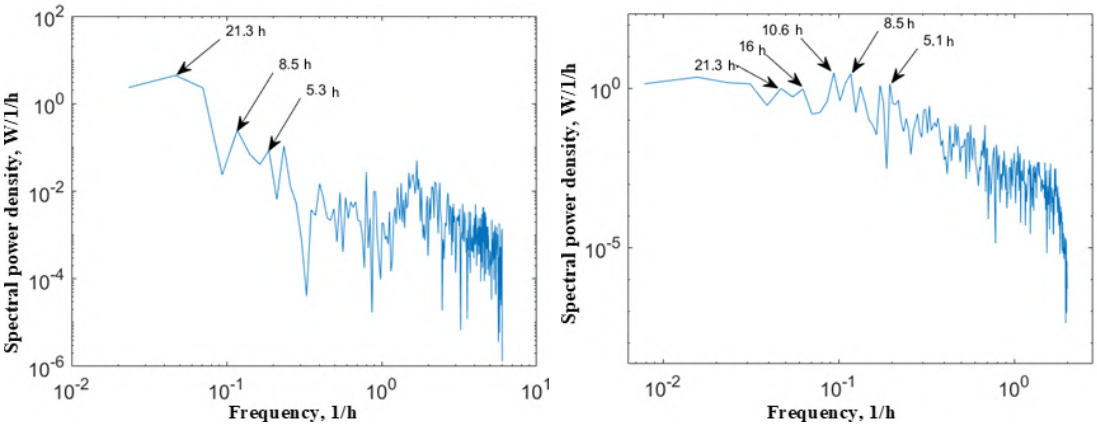

Figure 3: The spectral density of temperature in the station T1 in periods 08.07.2015–11.07.2015 (left) and 01.07.2015–01.08.2015 (right).

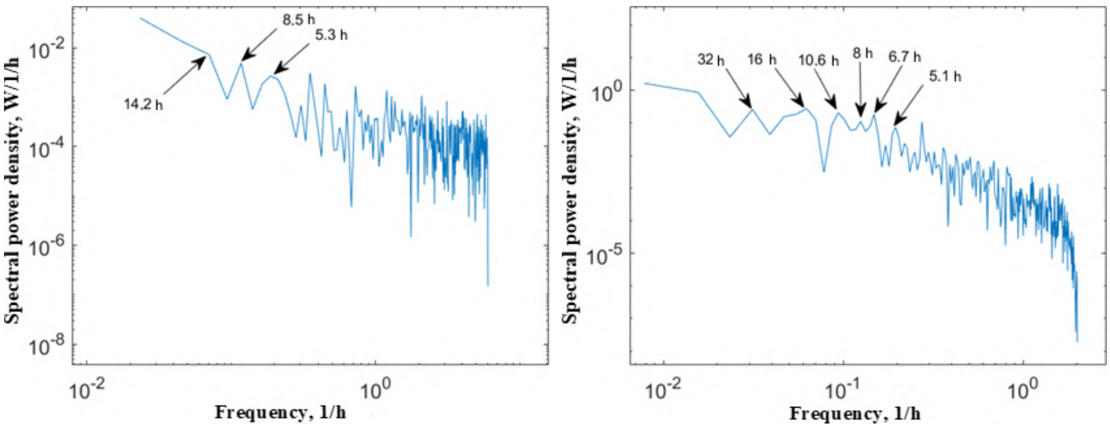

Figure 4: The spectral density of temperature in the station T2 in periods 08.07.2015–11.07.2015 (left) and 01.07.2015–01.08.2015 (right).

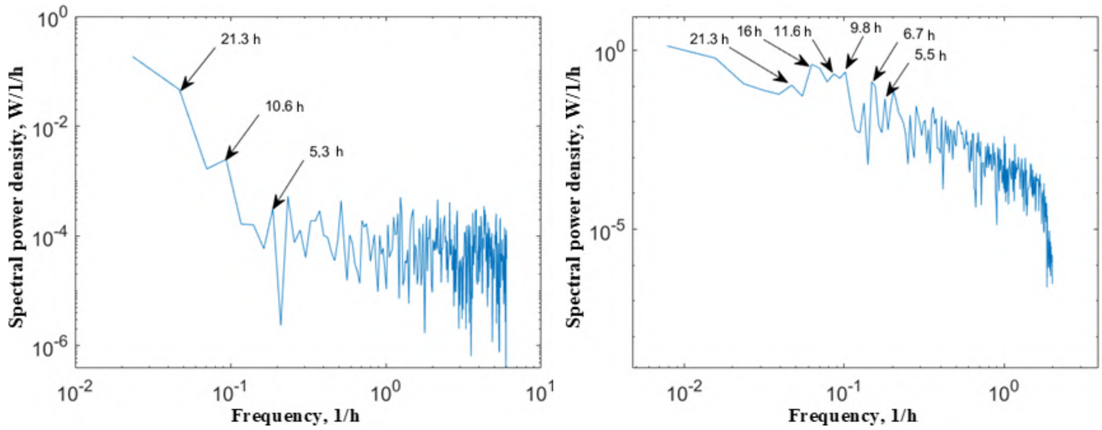

Figure 5: The spectral density of temperature in the station T4 in periods 08.07.2015–11.07.2015 (left) and 01.07.2015–01.08.2015 (right).

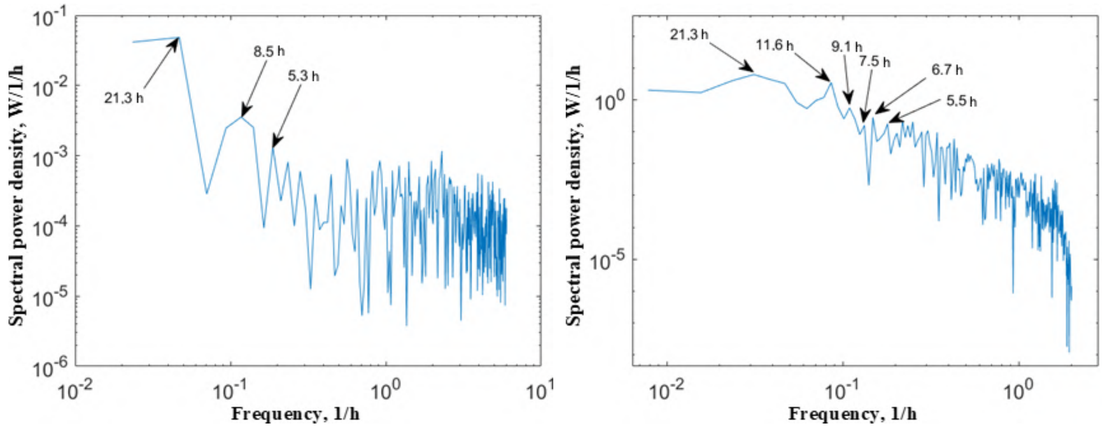

Figure 6: The spectral density of temperature in the station T7 in periods 08.07.2015–11.07.2015 (left) and 01.07.2015–01.08.2015 (right).

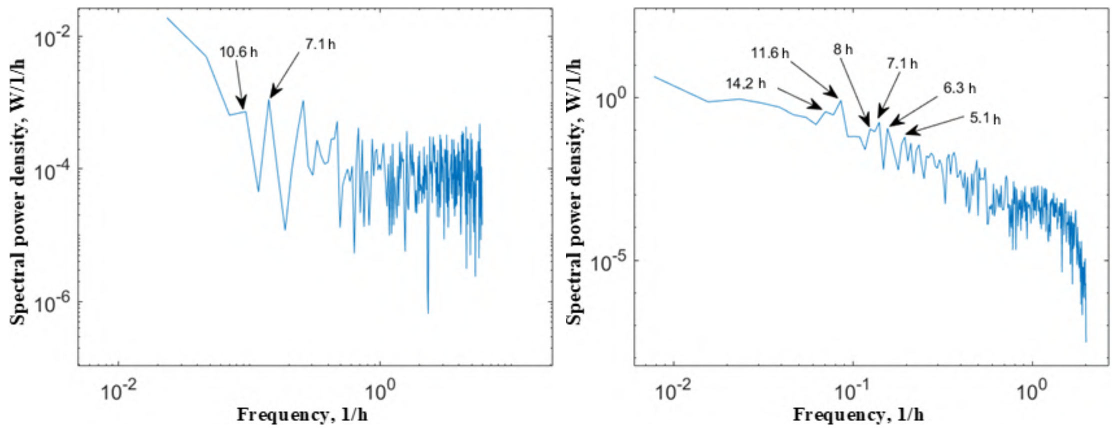

Figure 7: The spectral density of temperature in the station T8 in periods 08.07.2015–11.07.2015 (left) and 01.07.2015–01.08.2015 (right).

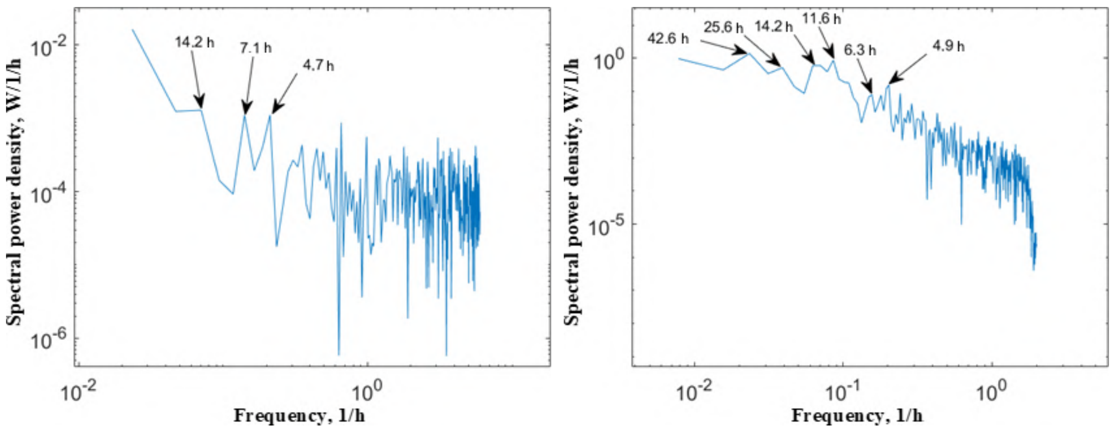

Figure 8: The spectral density of temperature in the station T9 in periods 08.07.2015–11.07.2015 (left) and 01.07.2015–01.08.2015 (right).

The spectral estimations of temperature of 2013–2014 are presented in Tables 2 and 3.

In summer 2013, 2014 and 2015, the spectral analysis of the temperature data showed the presence of maxima at a frequencies corresponding to long-time periods of 32, 26.5, 21.3, 14.2 h. In 2015 in station T10 were identified maximum corresponding to period of 42.6 h, that multiple 21.3 h. It should be emphasized the presence at the same time of maxima at frequencies corresponding to long periods, and periods 2–4 times smaller: 42.6 h — 21.3 h, 32 h — 16 h, 26.5 h — 13.3 h, 14.2 h — 21.3 h.

Table 2

The spectral estimations of temperature of 2014.

Frequency, 1/h	Period, h	Spectral power density, W/(1/h)	Frequency, 1/h	Period, h	Spectral power density, W/(1/h)
01.07.2015–21.07.2015			19.07.2014–30.07.2014		
Station T3			Station T4		
0.03906	25.6	0.4086	0.03125	32	0.5518
0.04688	21.3	0.2974	0.04688	21.3	0.3595
0.07031	14.2	0.1158	0.0625	16	0.9857
0.09375	10.6	0.9203	0.07813	12.8	0.6905
0.1172	8.5	2.522	0.1094	9.1	2.228
0.1382	7.2	0.2607	0.1563	6.4	1.394
0.1797	5.6	0.2284			
Station T5					
0.03906	25.6	12.52			
0.0625	16	4.52			
0.0859	11.6	6.148			
0.1016	9.8	10.81			
0.1406	7.1	4.645			
0.1875	5.3	16.91			

Table 3
The spectral estimations of temperature of 2013.

Frequency, 1/h	Period, h	Spectral power density, W/(1/h)	Frequency, 1/h	Period, h	Spectral power density, W/(1/h)
03.07.2013–05.08.2013					
Station T2			Station T3		
0.0375	26.6	60.74	0.0375	26.6	44.62
0.04688	21.3	22.77	0.06094	16.4	11.2
0.075	13.3	14.82	0.07031	14.2	18.49
0.08437	11.8	31.83	0.08437	11.8	26.12
0.1125	8.8	23.79	0.1125	8.8	17.67
0.1453	6.9	11.2	0.1453	6.9	2.913
0.1875	5.3	2.842	0.1828	5.4	2.894
Station T4			Station T5		
0.0375	26.6	19.2	0.0375	26.6	25.89
0.06094	16.4	15.81	0.05156	19.4	3.271
0.075	13.3	24.26	0.075	13.3	7.235
0.08906	11.2	29.34	0.08437	11.8	20.77
0.09844	10.1	17	0.1078	9.2	24.13
0.1125	8.8	14.01	0.1266	7.9	16.67
0.1453	6.9	4.523	0.1453	6.9	4.009
0.1828	5.4	4.711	0.1828	5.4	5.497

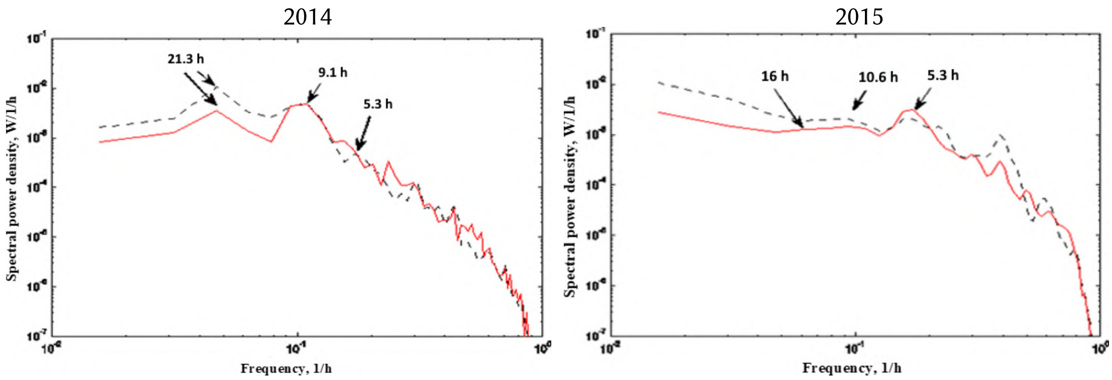

Figure 9: The spectral power of current velocity in the summer of 2014 and 2015.

The spectral estimates of temperature are consistent with the spectral estimates of the current velocity in lake Shira (Figure 9). These spectral estimates were presented in work [4].

4. Conclusions

The spectral analysis of the temperature data of summer 2013, 2014 and 2015 were allowed determining a period of internal waves in lake Shira. The spectral estimates of temperature are consistent with the spectral estimates of the current velocity. Based on spectral analysis over a period of three years, we can expect the presence of internal waves of such periods in lake Shira in other years.

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