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MARINE PHYSICS

On the Possibility of Forecasting the Long-Term Air Temperature Variability that Determines the Hydrophysical Structure and Ecology of the Black Sea Waters

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Abstract—Periods and amplitudes of long-term temperature fluctuations were obtained using the methods of spectral analysis and filtration of secular time series of the air temperature at 13 hydrometeorological stations in the Black Sea region. The prognostic calculations of the long-term air temperature variability are based on the results of processing of time series. The calculations of the air temperature agree with the data of observations. The possibility of the long-term air temperature variability prediction is shown.

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1. INTRODUCTION

The thermal conditions of the atmosphere represent one of the most important climatic factors that form the vertical hydrological structure of the Black Sea and determine the seasonal and interannual variability, as well as numerical values of the hydrophysical parameters [10, 12, 20]. The air temperature over the sea surface strongly determines the variability of hydrophysical processes, especially in the winter during the intrusion of cold continental air masses (polar continental or even Arctic) [5, 22]. The downwelling of anomalously cold oxygen saturated surface waters and the formation of the cold intermediate layer (CIL) occurs as a result of cooling and vertical density convection [9, 16–20].

During the density convection, the descending surface waters interact with deep anoxic waters oxidizing hydrogen sulfate. The lower the air temperature in the winter, the more intense the convection and oxidizing of hydrogen sulfate, which facilitates ecological conditions and bioproductivity of waters. Thus, cold and, especially, anomalously cold winters are very favorable in the ecological respect. During warm winters, the convection is weak and the interaction between the surface oxic waters and deep anoxic waters (hence, the oxidizing of hydrogen sulfate) decreases, which makes the ecological condition of the waters worse [11, 18, 19].

In the summer, the main factor of the hydrological structure formation is the flux of solar radiation to the sea surface, while the atmospheric thermal conditions play a secondary role. However, the interannual air temperature fluctuations (at a practically constant flux of the solar radiation[1] influence the formation of the summer hydrological structure [15, 17]. The main elements of the summer structure are the upper quasi-homogeneous layer (UQL) with a thickness of 10–15 m and a water temperature up to 25–26°C and the underlying thick seasonal thermocline (and pycnocline) preventing vertical mixing. The higher the air temperature in the summer, the greater the warming of the UQL and the vertical density gradient layer under this layer and the stronger its isolation from the underlying waters [21]. Owing to these factors, dissolved and suspended pollutants are concentrated in the UQL, thus, worsening the ecological conditions in the waters [11].

Thus, the air temperature is one of the main factors determining the variability of the hydrophysical processes, the variability of the hydrological and hydrochemical characteristics, and the ecological conditions of the waters. In this relation, the research and forecasting of the long-term variability of the atmospheric thermal conditions as the most important cause of the formation and variability of the hydrological structure and ecological condition of the Black Sea waters becomes necessary. This would make it possible to forecast anomalous conditions of the upper active layer of the sea and unfavorable ecological situations. In this paper, we estimate the possibility of prognostic calculations of the long-term variability of the monthly mean air temperature.

2. EXPERIMENTAL DATA AND METHODS FOR PROCESSING

Secular time series of the monthly mean air temperature values at 13 marine hydrometeorological stations (HMS) of the Black Sea (Table 1) were used as the experimental data, which were processed and analyzed. The goal of the processing was to determine the param-

[1] The solar radiation flux (solar constant) is equal to 1360 ± 20 W/m^2, and its variations do not exceed 1.5% [8].)

Table 1. Points of measurements of the air temperature and the duration of time series

Number	Hydrometeorological station	Time of measurement: beginning–end	Duration of the time series, years
1	Odessa	January 1894–December 1985	92
2	Nikolaev	January 1881–December 1983	103
3	Sevastopol	January 1882–December 1983	102
4	Yalta	January 1881–December 1983	103
5	Feodosiya	January 1881–December 1983	103
6	Kerch	January 1881–December 1982	102
7	Anapa	January 1899–December 1985	87
8	Novorossiisk	January 1872–December 1983	112
9	Gelendzhik	January 1922–December 2003	82
10	Tuapse	January 1903–December 1988	86
11	Sochi	January 1877–December 1985	109
12	Poti	January 1912–December 1985	74
13	Batumi	January 1882–December 1985	104

eters of the fluctuations (periods, amplitudes, and phases), which are necessary for prognostic calculations.

The long-term variability of the air temperature is characterized by a wide range of periods (from 2–3 to 50–55 years) [10]. The initial time series were preliminary divided into two parts—long-period and short-period (conventionally)—to obtain more precise results of the processing. The long-period part was obtained by smoothing the initial data of the measurements using the method of a running mean with a period of five years. As a result, the short-period fluctuations were suppressed. Next, the smoothed time series were subtracted from the initial time series. The residual time series (differences) obtained contained only the short-period fluctuations (2–5 years). After this procedure, spectral analysis and filtration were applied both to the smoothed and residual time series.

The processing consisted of two stages. First, spectral analysis was applied to the time series. Different methods of spectral analysis were used [1, 3, 4, 14] to obtain reliable results, which were compared and summarized. However, spectral analysis allows us to determine only one parameter of the fluctuations—their periods. In the low frequency spectral range, in which the sampling time is large, the periods are estimated approximately. Therefore, at the second stage, in order to more precisely estimate the periods distinguished by the spectral analysis and also to determine the amplitudes and phases of the fluctuations, filtration methods of time series were applied [6, 13]. The results of the spectral analysis were used as test periods during the filtration.

Thus, the composition of the main fluctuations forming the regime of the long-term variability of the air temperature was determined as a result of joint application of the methods of spectral analysis and filtration of time series. Their parameters were also determined.

3. ANALYSIS OF THE RESULTS OF THE PROCESSING

The prognostic calculations require an estimate of the contribution (variances) of the long-period and short-period fluctuations to the total variability of the air temperature. The main statistical parameters of the time series of monthly mean temperatures are given in Table 2. It is seen from the comparison of the root-mean-square deviations that the contribution of the short-period fluctuations in the summer is 1.7–1.8 times greater and in the winter is 2.1–2.2 times greater than the contribution of the long-period fluctuations.

The results of processing of the monthly mean time series of temperatures summarized over different HMS with a duration exceeding 100 years are given in Table 3. The periods and phases of the fluctuations at all the HMS are practically the same; therefore, only their mean values for each month are presented in the table. The composition of the fluctuations is characterized by seasonal variations. This fact is most likely related to the seasonal reconstruction of the atmospheric circulation.

The amplitudes of the fluctuations (for the same periods) at all the points of the Black Sea coast are different. The winter fluctuations are characterized by the greatest amplitudes. In the summer, they decrease by a factor of 1.5–2 and reach the minimal values. The spatial distribution of the amplitudes of the same periods depends on the geographical latitude and point of observation (at the northern HMS, the amplitudes are

Table 2. Long-term monthly mean values of the air temperature and standard deviations of the initial (T_a°C ± σ_i, long-term (σ_{lt}), and short-period (σ_{sp}) time series

Hydrometeorological station	Month, Parameters	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Odessa	T_a°C ± σ_i	–2.2 ± 3.1	–1.5 ± 2.8	2.2 ± 2.0	8.4 ± 1.5	15.0 ± 1.6	19.3 ± 1.4	21.9 ± 1.4	21.4 ± 1.3	16.9 ± 1.5	11.3 ± 2.0	5.5 ± 2.3	0.6 ± 2.4
	σ_{lt}	1.2	1.2	0.9	0.8	0.8	0.6	0.7	0.6	0.6	0.9	1.1	1.1
	σ_{sp}	2.9	2.5	1.8	1.2	1.3	1.3	1.1	1.2	1.4	1.9	2.0	2.1
Nikolaev	T_a°C ± σ_i	–3.6 ± 3.4	–2.5 ± 3.1	2.2 ± 2.1	9.5 ± 1.8	16.5 ± 1.7	20.4 ± 1.5	22.8 ± 1.5	22.1 ± 1.6	16.9 ± 1.8	10.4 ± 2.2	4.2 ± 2.3	–0.8 ± 2.9
	σ_{lt}	1.4	1.5	1.0	1.0	0.9	0.6	0.8	0.8	0.7	1.0	1.1	1.3
	σ_{sp}	3.3	2.7	1.9	1.5	1.5	1.5	1.2	1.4	1.6	2.0	2.0	2.6
Sevastopol	T_a°C ± σ_i	2.7 ± 2.4	2.9 ± 2.5	5.4 ± 1.8	9.8 ± 1.4	15.0 ± 1.2	19.5 ± 1.2	22.3 ± 1.1	22.0 ± 1.1	18.0 ± 1.4	13.5 ± 1.9	8.8 ± 2.2	5.2 ± 2.3
	σ_{lt}	1.0	1.1	0.8	0.8	0.7	0.5	0.6	0.5	0.5	0.9	1.1	1.0
	σ_{sp}	2.3	2.3	1.7	1.2	1.0	1.1	0.9	1.0	1.3	1.7	1.9	2.1
Yalta	T_a°C ± σ_i	3.9 ± 1.9	4.0 ± 1.9	6.0 ± 1.4	10.4 ± 1.2	15.6 ± 1.2	20.3 ± 1.3	23.6 ± 1.4	23.4 ± 1.3	19.1 ± 1.4	14.1 ± 1.8	9.5 ± 1.8	6.2 ± 1.8
	σ_{lt}	0.8	0.8	0.7	0.6	0.6	0.5	0.5	0.6	0.5	0.9	0.9	0.9
	σ_{sp}	1.7	1.7	1.4	1.0	1.0	1.2	1.3	1.2	1.3	1.6	1.6	1.6
Feodosiya	T_a°C ± σ_i	0.5 ± 3.0	0.7 ± 3.1	4.3 ± 1.8	9.8 ± 1.5	15.8 ± 1.3	20.5 ± 1.3	23.7 ± 1.2	23.1 ± 1.2	18.5 ± 1.5	13.0 ± 2.0	7.5 ± 2.2	3.4 ± 2.6
	σ_{lt}	1.2	1.4	0.9	0.7	0.7	0.5	0.6	0.6	0.6	1.0	1.0	1.2
	σ_{sp}	2.9	2.8	1.7	1.3	1.1	1.3	1.0	1.1	1.4	1.8	2.0	2.3
Kerch	T_a°C ± σ_i	–0.6 ± 3.1	–0.4 ± 3.0	3.2 ± 1.8	9.1 ± 1.5	15.7 ± 1.3	20.4 ± 1.4	23.7 ± 1.2	23.1 ± 1.1	18.2 ± 1.5	12.4 ± 2.0	6.8 ± 2.2	2.5 ± 2.7
	σ_{lt}	1.4	1.3	0.8	0.8	0.7	0.6	0.5	0.6	0.5	0.9	1.0	1.3
	σ_{sp}	3.0	2.8	1.7	1.2	1.1	1.3	0.9	1.0	1.4	1.7	2.0	2.4
Anapa	T_a°C ± σ_i	1.8 ± 2.9	1.9 ± 3.2	5.0 ± 2.0	10.3 ± 1.5	15.6 ± 1.2	20.2 ± 1.2	23.2 ± 1.1	22.9 ± 1.2	18.1 ± 1.4	12.8 ± 2.1	8.0 ± 2.4	4.2 ± 2.7
	σ_{lt}	1.2	1.4	0.9	0.8	0.6	0.5	0.6	0.6	0.6	1.0	1.1	1.2
	σ_{sp}	2.7	2.9	1.9	1.2	1.1	1.1	1.0	1.0	1.4	1.7	2.2	2.4
Novorossiisk	T_a°C ± σ_i	2.6 ± 2.8	2.9 ± 2.8	5.8 ± 2.0	10.9 ± 1.5	16.1 ± 1.2	20.5 ± 1.4	23.7 ± 1.2	23.7 ± 1.3	19.3 ± 1.6	14.2 ± 2.1	8.9 ± 2.4	5.2 ± 2.5
	σ_{lt}	1.1	1.2	1.0	0.8	0.6	0.6	0.6	0.6	0.6	1.0	1.1	1.1
	σ_{sp}	2.7	2.5	1.9	1.3	1.1	1.3	1.0	1.1	1.6	1.8	2.1	2.3
Gelendzhik	T_a°C ± σ_i	4.2 ± 2.8	4.3 ± 2.4	6.4 ± 1.8	11.0 ± 1.4	16.0 ± 1.1	20.5 ± 1.3	23.8 ± 1.2	23.9 ± 1.3	19.6 ± 1.6	14.4 ± 1.9	10.2 ± 2.3	6.4 ± 2.5
	σ_{lt}	1.1	1.0	0.9	0.7	0.5	0.6	0.5	0.6	0.7	1.0	1.1	1.1
	σ_{lt}	2.5	2.2	1.6	1.2	1.0	1.1	1.1	1.1	1.4	1.6	2.0	2.2
Tuapse	T_a°C ± σ_i	4.7 ± 2.4	4.8 ± 2.3	7.2 ± 1.8	11.4 ± 1.4	16.2 ± 1.2	20.3 ± 1.2	23.1 ± 1.1	23.3 ± 1.3	19.6 ± 1.5	14.8 ± 1.8	10.7 ± 2.0	6.8 ± 2.1
	σ_{lt}	1.1	1.0	0.9	0.7	0.6	0.5	0.5	0.6	0.7	0.9	1.0	1.1
	σ_{lt}	2.1	2.1	1.6	1.2	1.1	1.1	1.1	1.1	1.3	1.6	1.8	1.8
Sochi	T_a°C ± σ_i	6.0 ± 2.0	6.0 ± 2.2	8.1 ± 1.8	11.7 ± 1.5	16.2 ± 1.2	20.1 ± 1.2	22.9 ± 1.0	23.0 ± 1.1	19.7 ± 1.4	15.7 ± 1.8	11.7 ± 2.0	8.3 ± 1.9
	σ_{lt}	1.0	0.9	0.9	0.7	0.6	0.5	0.4	0.5	0.6	0.8	1.1	0.9
	σ_{lt}	1.9	2.0	1.6	1.3	1.0	1.1	0.9	1.0	1.3	1.6	1.6	1.6
Poti	T_a°C ± σ_i	6.1 ± 2.0	6.5 ± 1.9	8.8 ± 1.7	12.3 ± 1.3	16.5 ± 1.0	20.4 ± 1.1	23.0 ± 0.9	23.2 ± 1.1	20.3 ± 1.2	16.1 ± 1.7	12.0 ± 1.6	8.0 ± 1.8
	σ_{lt}	0.9	0.8	0.8	0.6	0.5	0.5	0.4	0.5	0.5	0.7	0.6	0.8
	σ_{lt}	1.8	1.8	1.5	1.2	0.9	1.0	0.8	1.0	1.2	1.5	1.5	1.7
Batumi	T_a°C ± σ_i	6.9 ± 2.0	6.8 ± 2.0	8.3 ± 1.7	11.4 ± 1.3	16.0 ± 1.2	20.2 ± 1.2	22.8 ± 0.9	23.0 ± 1.1	20.1 ± 1.3	16.1 ± 1.6	12.3 ± 1.7	9.2 ± 1.9
	σ_{lt}	0.9	0.8	0.8	0.6	0.6	0.5	0.4	0.5	0.5	0.6	0.7	1.0
	σ_{lt}	1.9	1.9	1.5	1.1	1.1	1.1	0.7	0.9	1.3	1.5	1.6	1.6

Table 3. Parameters (periods P, initial phases φ_0, and amplitudes A_T °C) of long-term fluctuations of the air temperature (monthly values)

Number of the hydrometeorological station (according to Table 1)										Number of the hydrometeorological station (according to Table 1)									
P, years	φ_0, year	2	3	4	5	6	8	11	13	P, years	φ_0, year	2	3	4	5	6	8	11	13
		Amplitudes (A_T °C)										Amplitudes (A_T °C)							
January										February									
48.0	1905	1.15	0.83	0.66	1.01	1.19	0.94	0.79	0.74	47.3	1891	0.85	0.65	0.50	0.79	0.78	0.70	0.51	0.46
19.7	1896	1.38	1.00	0.79	1.21	1.43	1.13	0.95	0.88	33.6	1894	0.89	0.68	0.52	0.83	0.82	0.74	0.53	0.48
12.4	1897	0.73	0.53	0.42	0.64	0.75	0.60	0.50	0.46	19.3	1897	0.93	0.72	0.54	0.87	0.85	0.77	0.56	0.51
7.5	1885	0.57	0.42	0.33	0.50	0.59	0.47	0.40	0.37	11.4	1899	0.81	0.62	0.47	0.75	0.74	0.67	0.48	0.44
4.5	1886	2.57	1.80	1.40	2.25	2.30	2.06	1.46	1.43	7.7	1900	0.57	0.44	0.33	0.53	0.52	0.47	0.34	0.31
3.7	1895	3.03	2.19	1.65	2.65	2.71	2.43	1.73	1.69	5.0	1889	1.79	1.52	1.16	1.87	1.82	1.68	1.34	1.26
2.6	1895	1.92	1.35	1.05	1.69	1.72	1.54	1.10	1.08	3.7	1889	1.87	1.59	1.21	1.95	1.89	1.74	1.40	1.31
2.1	1896	1.65	1.16	0.90	1.44	1.47	1.32	0.94	0.92	2.8	1895	2.02	1.71	1.31	2.11	2.04	1.88	1.51	1.42
										2.2	1895	1.79	1.52	1.16	1.87	1.82	1.67	1.34	1.25
March										April									
53.7	1906	0.54	0.46	0.39	0.48	0.44	0.54	0.48	0.44	50.8	1905	0.49	0.41	0.35	0.36	0.42	0.41	0.35	0.30
24.9	1911	0.57	0.49	0.41	0.51	0.46	0.57	0.51	0.46	25.7	1885	0.55	0.46	0.38	0.40	0.46	0.45	0.39	0.34
19.2	1885	0.59	0.51	0.43	0.53	0.48	0.59	0.53	0.48	16.7	1885	0.60	0.50	0.42	0.44	0.51	0.50	0.42	0.37
12.6	1901	0.65	0.55	0.46	0.58	0.53	0.65	0.58	0.53	12.8	1899	0.60	0.50	0.42	0.44	0.51	0.50	0.42	0.37
7.6	1884	0.35	0.30	0.25	0.31	0.29	0.35	0.31	0.29	7.8	1897	0.37	0.31	0.25	0.27	0.31	0.30	0.26	0.22
4.9	1891	0.98	0.87	0.72	0.91	0.88	0.98	0.84	0.80	4.9	1889	0.93	0.76	0.64	0.81	0.78	0.79	0.83	0.70
3.7	1891	1.96	1.74	1.44	1.82	1.76	1.96	1.67	1.60	3.2	1895	0.97	0.80	0.66	0.84	0.81	0.83	0.87	0.73
2.9	1893	1.19	1.05	0.87	1.10	1.06	1.19	1.01	0.96	2.7	1895	1.05	0.86	0.72	0.91	0.88	0.90	0.94	0.80
2.1	1885	1.03	0.91	0.75	0.96	0.92	1.03	0.88	0.84	2.2	1894	1.10	0.89	0.75	0.95	0.92	0.93	0.97	0.83
May										June									
34.3	1885	0.51	0.38	0.38	0.39	0.39	0.32	0.32	0.34	50.0	1890	0.18	0.15	0.16	0.15	0.18	0.19	0.16	0.16
20.2	1885	0.54	0.39	0.39	0.40	0.41	0.34	0.33	0.36	32.0	1913	0.26	0.22	0.24	0.22	0.27	0.28	0.23	0.24
16.4	1903	0.54	0.39	0.39	0.40	0.41	0.34	0.33	0.36	17.1	1884	0.42	0.36	0.38	0.36	0.44	0.45	0.37	0.38
12.2	1906	0.49	0.36	0.36	0.37	0.37	0.31	0.30	0.32	12.2	1887	0.38	0.33	0.36	0.33	0.40	0.42	0.34	0.36
7.6	1897	0.34	0.25	0.25	0.26	0.26	0.22	0.21	0.23	7.7	1890	0.37	0.32	0.34	0.32	0.39	0.40	0.33	0.34
4.3	1891	1.36	0.91	0.91	1.03	1.03	1.05	0.95	1.06	4.7	1891	0.99	0.75	0.80	0.84	0.84	0.83	0.73	0.70
3.5	1891	1.12	0.75	0.75	0.85	0.85	0.86	0.78	0.87	3.6	1892	1.45	1.09	1.17	1.22	1.22	1.21	1.07	1.03
2.6	1887	0.88	0.59	0.59	0.66	0.67	0.68	0.61	0.68	2.8	1882	0.99	0.75	0.80	0.83	0.84	0.83	0.73	0.70
2.1	1885	0.63	0.42	0.42	0.48	0.48	0.49	0.45	0.50	2.2	1883	0.70	0.53	0.57	0.59	0.59	0.59	0.52	0.50

Table 3. (Contd.)

P, years	φ_0, year	2	3	4	5	6	8	11	13
		Amplitudes (A_T °C)							
		July							
49.3	1926	0.19	0.14	0.18	0.16	0.13	0.15	0.11	0.10
31.9	1924	0.46	0.35	0.45	0.38	0.31	0.37	0.26	0.25
16.2	1903	0.52	0.40	0.51	0.43	0.36	0.42	0.30	0.28
12.5	1895	0.50	0.38	0.49	0.42	0.34	0.40	0.28	0.27
7.7	1896	0.42	0.32	0.41	0.35	0.29	0.34	0.24	0.23
5.1	1890	0.71	0.51	0.65	0.57	0.53	0.58	0.51	0.42
4.2	1890	0.71	0.52	0.66	0.57	0.53	0.59	0.51	0.43
3.1	1895	0.67	0.49	0.63	0.54	0.51	0.56	0.49	0.40
2.5	1891	0.67	0.49	0.62	0.54	0.51	0.56	0.49	0.40
2.1	1887	0.60	0.44	0.56	0.48	0.45	0.50	0.44	0.36
		September							
30.6	1916	0.27	0.22	0.22	0.24	0.22	0.26	0.24	0.20
19.9	1920	0.38	0.31	0.31	0.33	0.31	0.40	0.34	0.28
15.5	1906	0.45	0.36	0.36	0.39	0.36	0.44	0.40	0.33
11.5	1897	0.38	0.31	0.31	0.33	0.31	0.40	0.34	0.28
7.5	1908	0.32	0.26	0.26	0.28	0.26	0.32	0.29	0.24
4.5	1892	1.44	1.16	1.16	1.25	1.25	1.36	1.14	1.12
3.5	1896	1.26	1.02	1.02	1.10	1.10	1.19	0.99	0.98
2.6	1890	1.04	0.84	0.84	0.90	0.90	0.98	0.82	0.80
2.2	1891	0.77	0.62	0.62	0.66	0.66	0.73	0.60	0.60
		November							
45.8	1883	0.68	0.69	0.57	0.64	0.62	0.67	0.67	0.42
19.7	1905	0.88	0.91	0.74	0.84	0.81	0.88	0.88	0.55
11.9	1914	0.74	0.76	0.62	0.70	0.68	0.73	0.73	0.46
8.3	1903	0.65	0.66	0.55	0.62	0.59	0.64	0.64	0.40
5.5	1890	1.08	1.07	0.88	1.10	1.11	1.17	0.91	0.88
4.5	1890	0.86	0.86	0.71	0.88	0.89	0.94	0.72	0.70
3.4	1893	1.40	1.39	1.15	1.44	1.44	1.53	1.18	1.14
2.8	1896	1.24	1.23	1.01	1.27	1.27	1.35	1.04	1.01
2.1	1895	0.80	0.80	0.66	0.83	0.83	0.88	0.68	0.66

P, years	φ_0, year	2	3	4	5	6	8	11	13
		Amplitudes (A_T °C)							
		August							
49.5	1932	0.52	0.34	0.40	0.42	0.36	0.40	0.34	0.32
30.7	1923	0.41	0.27	0.31	0.33	0.29	0.31	0.27	0.25
16.2	1904	0.43	0.28	0.33	0.35	0.30	0.33	0.28	0.26
12.5	1899	0.37	0.24	0.28	0.29	0.26	0.28	0.24	0.22
8.3	1908	0.43	0.28	0.33	0.35	0.30	0.32	0.28	0.26
4.3	1890	1.20	0.79	0.93	0.90	0.82	0.93	0.78	0.73
3.1	1890	1.00	0.66	0.78	0.75	0.69	0.78	0.65	0.61
2.6	1886	0.96	0.63	0.74	0.72	0.66	0.74	0.62	0.58
2.2	1885	0.84	0.55	0.65	0.62	0.58	0.65	0.55	0.50
		October							
32.5	1924	0.77	0.72	0.68	0.79	0.74	0.85	0.65	0.46
16.4	1916	0.61	0.57	0.54	0.63	0.59	0.67	0.52	0.36
10.9	1905	0.67	0.62	0.58	0.68	0.64	0.73	0.56	0.39
7.8	1906	0.61	0.57	0.54	0.63	0.59	0.67	0.52	0.36
4.3	1895	1.46	1.27	1.19	1.31	1.29	1.33	1.15	1.12
3.6	1889	1.40	1.22	1.15	1.26	1.24	1.28	1.11	1.08
2.8	1892	1.56	1.36	1.28	1.40	1.38	1.43	1.23	1.21
2.1	1891	0.97	0.84	0.80	0.87	0.85	0.89	0.76	0.75
		December							
50.0	1902	0.88	0.68	0.54	0.79	0.85	0.71	0.57	0.63
24.5	1905	0.81	0.62	0.49	0.73	0.77	0.65	0.52	0.58
16.4	1911	0.55	0.42	0.33	0.50	0.53	0.45	0.35	0.40
12.4	1912	0.84	0.65	0.51	0.76	0.81	0.68	0.54	0.61
7.1	1893	0.59	0.45	0.36	0.53	0.56	0.48	0.38	0.42
4.7	1891	1.14	0.89	0.70	1.00	1.04	1.02	0.70	0.71
3.5	1893	1.70	1.34	1.05	1.51	1.56	1.53	1.05	1.07
2.9	1901	1.56	1.23	0.96	1.38	1.43	1.40	0.96	0.98
2.4	1891	1.71	1.34	1.05	1.50	1.55	1.52	1.05	1.06
2.1	1892	0.99	0.78	0.61	0.88	0.90	0.89	0.61	0.62

Table 4. Variation coefficients of the periods (K_P) and amplitudes (K_A) of the fluctuations

Groups of periods*	Long-period							Short-period			
from to	53.7 45.8	34.3 30.6	25.7 24.5	20.2 19.2	17.1 15.5	12.8 10.9	8.3 7.1	4.9 4.1	3.8 3.1	2.9 2.5	2.3 2.1
K_P	0.02	0.05	0.09	0.10	0.11	0.15	0.16	0.21	0.25	0.27	0.30
K_A	0.18	0.25	0.30	0.32	0.42	0.46	0.48	0.50	0.52	0.58	0.60

Note: * Data from Table 3.

greater, and, at the southern stations, they are smaller) and on the local orographic conditions.

The results obtained (Tables 2 and 3) were the basis for the calculations of the long-term variability of the air temperature.

4. ESTIMATE OF THE ACCURACY OF THE TEMPERATURE CALCULATIONS

The prognostic calculation is based on the approximation of the fluctuations distinguished as a result of processing (Table 3) by harmonics (sinusoids) with constant (mean) periods and amplitudes. Thus, the accuracy of the prognostic calculations depends on the stability of the periods and amplitudes of the fluctuations distinguished. If the fluctuations are unstable, they will episodically deviate in phase and amplitude from the approximating sinusoids with constant periods and amplitudes, which cause errors in the calculations. The variation coefficient, i.e., the ratio of the root-mean-square deviations of the periods and amplitudes to their mean values, was accepted as a criterion of the stability of the empiric fluctuations. The summarized variation coefficients for all the observed periods of the fluctuations are given below.

As follows from Table 4, the variation coefficients increase (and the stability of the fluctuations correspondingly decreases) with decreasing periods, especially for short-period fluctuations. For example, in the range of long-period fluctuations, the variation coefficients vary from 0.02 to 0.16 for the periods and from 0.18 to 0.48 for the amplitudes. In the short-period range of fluctuations, they are equal to 0.21–0.30 and 0.050–0.60, respectively.

Test calculations showed that the long-period fluctuations are satisfactorily reproduced by sinusoids with constant (mean) periods and amplitudes and they can be considered quasiperiodic. On the contrary, the short-period fluctuations are not reproduced by harmonics with constant periods and amplitudes. Owing to the strong variability in the periods and especially in the amplitudes, frequent mismatches occur between them and the approximating harmonics, which caused large errors in the calculations. Due to instability, the character of the short-period fluctuations is irregular (random) and they should be qualified as statistical noise. In the prognostic calculations, such fluctuations are taken into account using statistical methods by means of their root-mean-square deviations [7].

Taking into account the above-mentioned estimates of the stability of the long-period and short-period fluctuations, the structure of the equations for the calculations is composed of three parts:

(1) Long-term mean (norm $\overline{T}_n$). If a real, statistically significant temperature trend exists, it is introduced instead of $\overline{T}_n$. In the case of processing secular time series of the temperature (Table 1), no clearly manifested trend was found, which agrees with the data in [2].

(2) The sum of the harmonics approximating long-period quasiperiodic fluctuations $\left(\sum_{i=1}^{n} A_i \sin q_i t\right)$.

(3) The contribution of the short-period fluctuations in the form of root-mean-square deviations σ_{sp} relative to the sum of the long-period fluctuations.

As an example, in Fig. 1, filtered fluctuations (curves *1*) and approximating harmonics (*2*) for January (HMS Theodossia) are shown. It is seen that the stability of the parameters of the fluctuations decreases with the decrease of the periods of the fluctuations: the fluctuations with periods of (a) 46 and (b) 20 years are relatively stable (*1*) and well approximated by the harmonics (*2*). The stability of the fluctuations with periods of (c) 13.3 and (d) 7.5 years decreases, which results in the partial episodic mismatch with the calculation harmonics. Thus, when the variability (variation coefficients) of the filtered fluctuations increases, it becomes more difficult to find an optimal version of their approximation. In general, as seen from Fig. 1e, the result of the model calculation (curve *4*) quite satisfactorily agrees with the initial smoothed time series (curve *3*).

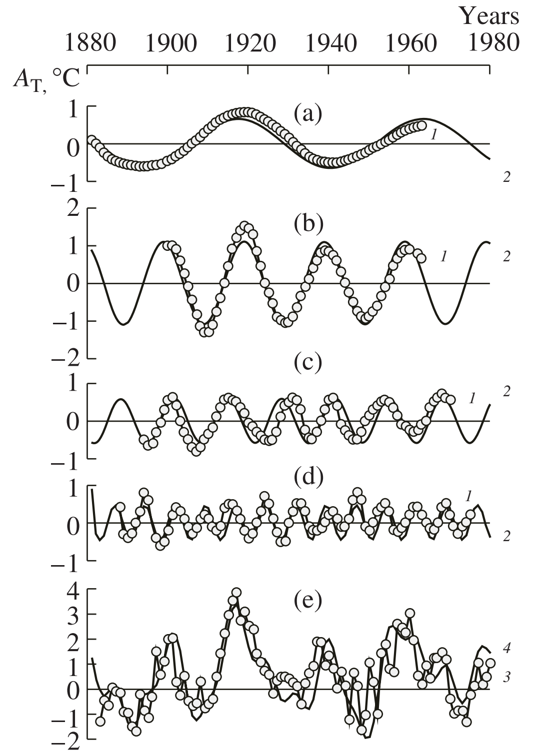

Fig. 1. Main periods (years) of long-term fluctuations of air temperature in January (Hydrometeorological station in Feodosiya): (a) 48.0, (b) 19.7, (c) 12.4, and (d) 7.5 years. *1*—Filtered fluctuations, *2*—approximating harmonics, and (e) comparison of the initial and smoothed time series (*3*) with the calculation (*4*).

This scheme was used to calculate the air temperature and to obtain the estimates of the accuracy of the calculations for the long-period and integrated fluctuations (with account for the short-period fluctuations).

The adequacy of the calculations was estimated by comparing the statistical parameters of the initial and calculated time series and by determining the probability of the errors of the calculations with an interval of 0.5°C.

The chronological evolutions of the initial smoothed temperature time series (*1*) and calculated long-period quasi-stationary time series (2) of the air temperature in January and July for the western (Sebastopol), central (Kerch), eastern (Novorossiysk), and southeastern (Batumi) parts of the Black Sea are shown in Fig. 2. It is seen from the figure that the calculated curves generally approximate quite satisfactorily the long-term evolution of the air temperature, which is synchronous over the entire basin of the Black Sea. Below, we present a comparison of the main statistical parameters of the initial and calculated time series of the air temperature.

As seen from Table 5, the statistical parameters of the initial and calculated time series of the temperature practically coincide. However, the main criterion of the adequacy of the calculation is the statistics of the errors,

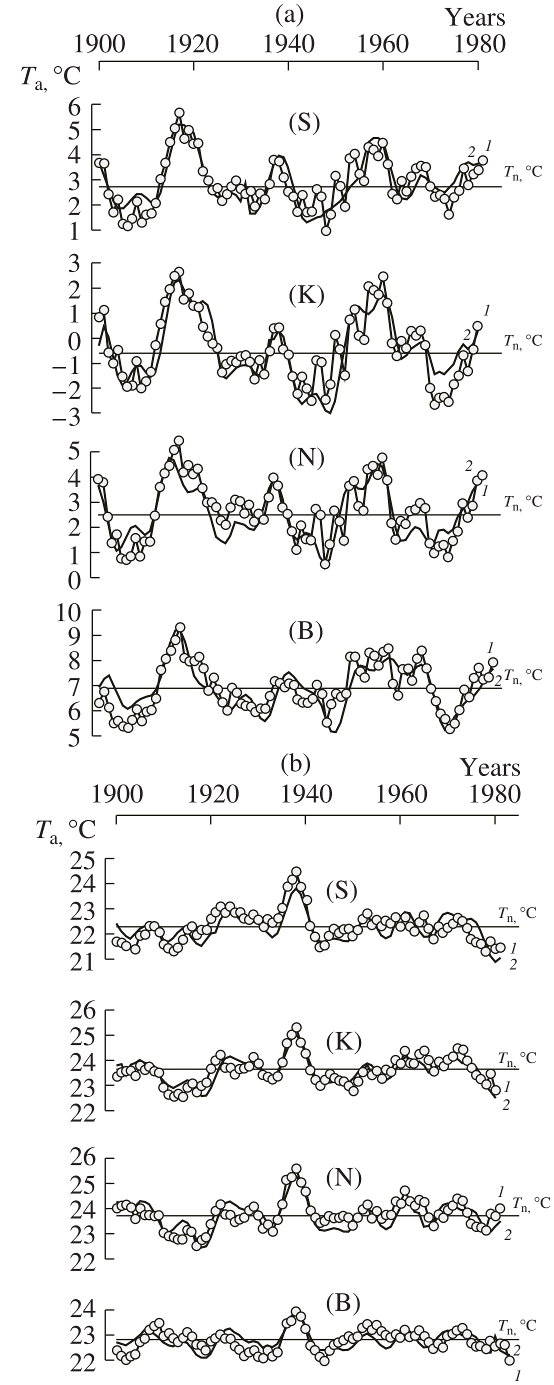

Fig. 2. Chronological graphs of the initial smoothed (*1*) and calculated long-period (*2*) fluctuations of the air temperature in (a) January and (b) July. Notations: Sevastopol (S), Kerch (K), Novorossiisk (N), and Batumi (B).

i.e., the differences between the initial and calculated values: $\Delta T = T_{ISTS} - T_{CLPTS}$.

It is seen from Table 6 that from 47 to 58% of the errors in the winter (January) and from 59 to 80% of the errors in the summer (July) do not exceed 0.5°C, while the probability of errors in the range less than 1°C is

Table 5. Mean values and root-mean-square deviations (T_a°C ± σ) of the initial smoothed time series (ISTS) and calculated long-period time series (CLPTS)

Month, Hydrometeorological station		Sevastopol	Kerch	Novorossiisk	Batumi
January	ISTS	2.72 ± 1.01	–0.61 ± 1.44	2.50 ± 1.14	6.90 ± 0.89
	CLPTS	2.72 ± 1.05	–0.62 ± 1.43	2.53 ± 1.13	6.85 ± 0.89
July	ISTS	22.28 ± 0.58	23.64 ± 0.52	23.71 ± 0.61	22.82 ± 0.41
	CLPTS	22.26 ± 0.58	23.62 ± 0.52	23.69 ± 0.61	22.80 ± 0.41

Table 6. Statistics of the errors in the calculations of the long-period fluctuatio

Month		January					July			
Hydrometeorological station, Error scale		0–0.5–1.0–1.5–2.0–2.5					0–0.5–1.0–1.5–2.0			
Sevastopol	DEPE%	51	37	9	3		59	32	9	
	IEP%	51	88	97	100		59	91	100	
Kerch	DEPE%	48	24	23	4	1	80	17	2	1
	IEP%	48	72	95	99	100	80	97	99	100
Novorossiisk	DEPE%	47	26	16	7	4	68	28	3	1
	IEP%	47	73	89	96	100	68	96	99	100
Batumi	DEPE%	58	32	9	1		65	31	4	
	IEP%	58	90	99	100		65	96	100	

Note: The error scale has a step of 0.5°C. DEPE is the differential empirical probability of the errors (recurrence). IEP is the integral empirical probability (reliability).

equal to 72–90% (in January) and 91–96% (in July), respectively. In the range 1.5–2.0°C, the probability of errors in the winter is equal to 1–7% and to 0–1% in the summer. On the basis of these estimates, the calculation of the long-term fluctuations of the air temperature can be considered satisfactory.

Next, we shall consider and estimate the possibility of calculation of integrated (long-period plus short-period) fluctuations with the addition of short-period fluctuations in the form of their root-mean-square deviations. A comparison of the initial measurements and calculated integrated time series is shown in Fig. 3.

As seen from Fig. 3, the graphs of the long-period fluctuations (*2*) reflect the smooth long-term variability of the temperature, i.e., the temperature background, which is superimposed by sharply varying short-period fluctuations that characterize the actual temperature variations (*1*). The root-mean-square deviations of the short-period fluctuations (*3* and *4*) show the zone of scattering of the calculated temperatures relative to the evolution of the long-period fluctuations.

Below, we present the estimates of the errors of the calculation of the integrated fluctuations, in which the differences ΔT°C falling beyond the calculated range of T_{CLPTS}°C ± σ_{sp} were assumed as errors.

It follows from Table 7 that from 63 to 77% of the calculated temperature values do not fall beyond the ± σ_{sp} limits. The probability of errors up to 0.5°C is 75–81% in January and 81–86% in July; the probability of errors up to 1°C is 83–92% and 92–95%, respectively; and the probability of errors greater than 1°C is 8–17% in January and 5–8% in July.

It is seen in Fig. 3 that the limiting values of the temperature (*1*) are correlated with its long-period evolution. For example, in the years with an increased (relative to the norm) temperature background (*2*), warm (W) and anomalously warm (AW) thermal conditions are observed significantly more frequently, whereas cold (C) and anomalously cold (AC) conditions appear significantly rarely. At the decreased background of the long-period variability, the C and AC conditions prevail over the W and AW conditions. A statistical estimate of this correlation is given in Table 8.

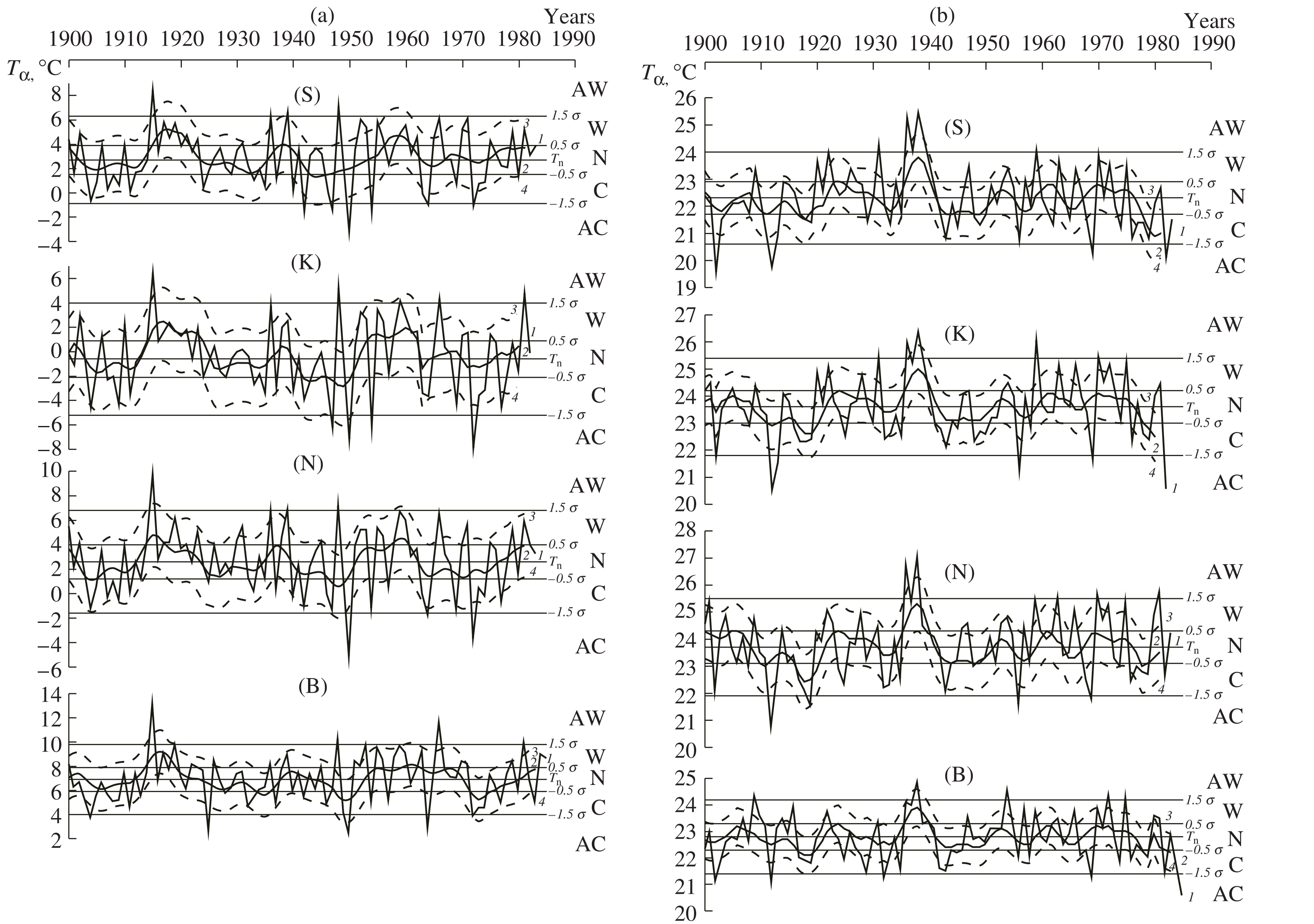

Fig. 3. Chronological graphs of the initial smoothed (*1*) and total calculated (*2*) time series of air temperatures in (a) January and (b) July. Notations: Sevastopol (S), Kerch (K), Novorossiisk (N), and Batumi (B). $\bar{T}_n$ is the average long-term value of the temperature (norm); and *3* and *4* are the $+\sigma_{sp}$ and $-\sigma_{sp}$ root-mean-square deviations of the short-period fluctuations (the dashed lines), respectively. The scale of the atmospheric thermal conditions relative to the norm ($\bar{T}_n$) in the gradations of the values of σ: the values in the range of ±0.5σ are related to the normal thermal conditions (N), the values from 0.5σ to 1.5σ are related to the warm conditions (W), the values >1.5σ are related to the anomalously warm conditions (AW), the values from –0.5σ to –1.5σ are related to the cold conditions (C), and the values <–1.5σ are related to the anomalously cold conditions (AC).

Table 7. Statistics of the errors in the calculations of the total fluctuations of the air temperature

Month		January							July					
Hydrometeorological station, Error scale		$0 \pm \sigma_{sp}$ 0.1–0.5–1.0–2.0–3.0–4.0–5.0							$0 \pm \sigma_{sp}$ 0.1–0.5–1.0–2.0–3.0					
Sevastopol	DEPE%	70	5	8	8	8	1		64	17	11	7	1	
	IEP%	70	75	83	91	99	100		64	81	92	99	100	
Kerch	DEPE%	73	7	6	5	5	3	1	67	17	8	8		
	IEP%	73	80	86	91	96	99	100	67	84	92	100		
Novorossiisk	DEPE%	73	4	10	6	3	3	1	64	22	9	5		
	IEP%	73	77	87	93	96	99	100	64	86	95	100		
Batumi	DEPE%	77	4	11	5	3			63	18	14	5		
	IEP%	77	81	92	97	100			63	81	95	100		

Table 8. Empirical probability (%) of the thermal conditions against the background of the long-term temperature evolution

Background below the norm					Norm					Background above the norm				
AC	C	N	W	AW	AC	C	N	W	AW	AC	C	N	W	AW
15	34	37	12	2	3	20	48	25	4	3	12	33	39	13

It is seen in Table 3 that, under the conditions of the decreased background of the temperature, the C (34%) and AC (15%) conditions are observed most frequently, whereas the probability of the W (12%) and AW (2%) conditions is three times smaller. When the temperature is close to the norm, the N conditions dominate (48%) and the probability of cold or warm conditions is two times smaller. In the case of an increased background, the greatest probability is characteristic of the W (39%) and AW (13%) conditions, which is 3.5 times as great as the probabilities of the C (12%) and AC (3%) conditions.

Thus, the calculations of the long-period (quasiperiodic) fluctuations with account for the root-mean-square deviations of the irregular (random) short-period fluctuations allow us to develop a background forecast of the long-term variability of the atmospheric thermal conditions over the Black Sea basin and to estimate the expected variations in the hydrological structure and ecological condition of the waters, which they cause.

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