Seasonal and Regional Variations of Water Temperature Synoptic Anomalies in the Northeastern Coastal Zone of the Black Sea

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Climatic annual cycle of root-mean-square (RMS) values of synoptic water temperature anomalies (SWTA) with daily discreteness is analyzed based on observations within 1977-2005 period at hydro-meteostations (HMS) in the northeastern part of the Black Sea.
It is shown that SWTA values are statistically associated with their negative mean values testifying the fact that upwelling is a predominant mechanism in generating synoptic water temperature anomalies. In summer of synoptic variability of water temperature increases significantly from the north to south and in winter – from the south to north.
Five modes of the intra-annual variability according to the linear tends of SWTA values are revealed. Their phases and parameters are close the steep HMSs (Sochi, Tuapse and Gelendzhik), but are considerably different from the values in the autumn-winter period in Anapa HMS. The first (I), winter mixing mode is the longest one (late November – March) and is characterized by the lowest RMS values of SWTA. Spring growth mode (II) id characterized by a pronounced positive linear trend with a simultaneous decrease in the absolute values of the dispersion relative to the trend. In summer, there are two types of modes, which are characterized by high absolute levels of the same value, but different from each other. One of them (III) can be called "upwelling" mode and another (IV) – mode of "thermal stabilization". Mode (V) starts with the autumn cooling of the sea water. During this mode there is a marked decrease of SWTA values and an increase of their dispersion.
It is noted that in the shallow water area (Anapa HMS) the phase shift and mode duration is observed due to the lower thermal inertia of the water column, as well as the unique mode associated with a sharp decrease in wind activity in mid-February is marked.

Keywords: upwelling, current, wind, the Black Sea, synoptic variability, sea surface temperature

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Introduction. Synoptic variability with time scales from the inertial period to the season is one of the five major time spans of variations of the water state of the oceans and seas along with inter-annual (long-term), seasonal, daily and short-period ranges [1]. In the coastal area of the ocean and seas, including continental shelf and a slope, the main processes that form synoptic variability are upwelling/downwelling of various nature, synoptic eddies and coastal trapped waves (CTW). Specialized expeditionary and theoretical research of these processes carried out in 1970 – 1980 off North and South America, Africa, Australia and Western Europe convincingly showed the close genetic relationship between them [1 – 8]. Herein the wind-driven coastal upwelling/downwelling almost always gives the start (starts up the mechanism) to CTW that spread along the coast (leaving it in the Northern Hemisphere to the right) as alternating areas of divergence/convergence of alongshore synoptic currents. Wave upwelling/downwelling areas are connected with the aforementioned ones and spread in the same direction. In the process of this movement they can be 'pumped up' by the resonance wind effect [6, 8]. Periods of the wind-driven and wave upwelling vary in the range from several days to two to three weeks, the scale of alongshore heterogeneities – from tens to many hundreds of kilometers. Extremely wide and diverse application of knowledge and scientific importance of these processes causes their intensive research in most of the coastal regions of the oceans with an active economic activity. Herein not only the processes governing the dynamics of upwelling/downwelling synoptic phases: initial wind forcing, formations of the alongshore front zone and jet current, its countercurrent, its subsequent relaxation [9 – 11], but also the season [12, 13] and interannual variability of these phenomena.

In the Black Sea the first research of synoptic variability in the coastal area – wind effected phenomena – were performed 50 years ago [14 – 16]. The results of the first modern systematic research of the coastal upwelling and CTW off the South Coast of Crimea are described in [3, 14]. They showed a close similarity of the properties of these processes in the Black Sea and in the aforementioned regions of the World Ocean. In subsequent years, only separate expeditionary and model research of upwelling in the South Coast of Crimea [17 – 19] and in the area of the Zmeinyi Island [20] were carried out, and the evaluations of the total dispersion and spectra of the synoptic variability of currents in the north-eastern coast of the Black Sea [21, 22] were given. They showed that in the Caucasian Black Sea coastal zone the dispersion of velocity synoptic variations 1.5 – 2.5 times higher than the high-frequency one. Water temperature synoptic dispersion is 3 – 5 times higher than the high-frequency one. The variability of the spectra significant peaks at periods of 12; 8 –10; 6; 4 – 2 days were allocated.

Also it should be noted that specific studies of climate (long-time average annual) seasonal variations in the water temperature synoptic variability in the north-eastern part of the Black Sea coastal zone, similar to the research performed on the western coast of North and South America [12, 13], as well as in the South Coast of Crimea [8], has not been carried out yet. The purpose of this work is to fill this gap, using historical data of systematic coastal observations at the HMS in the specified area of the Black Sea.

Material and Methods. Major primary data for the present research were the results of long-term observations of the weather (primarily, wind speed and direction) and hydrological (temperature and salinity) characteristics at the Black Sea HMS, such as Anapa, Gelendzhik, Tuapse and Sochi in 1977 – 2005 (Fig. 1).

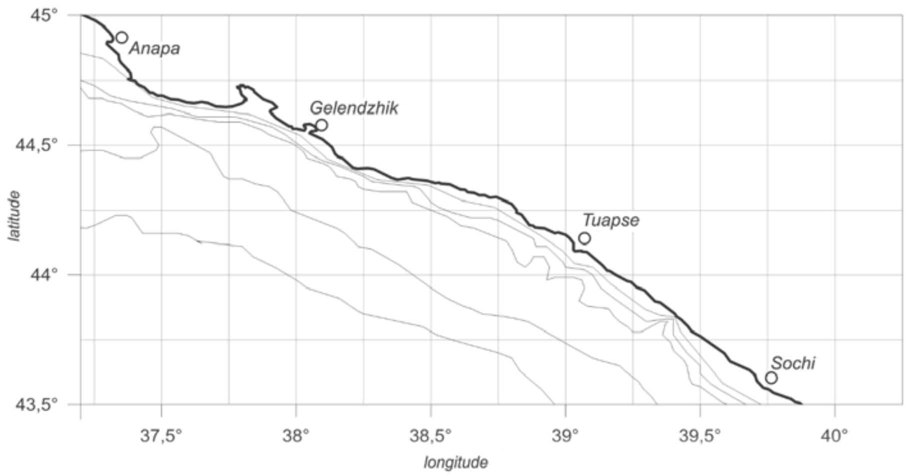

Fig. 1. Researched area and HMS allocation. The isobaths 50, 100, 200, 1000 and 1500 m are shown

For generalized climate feature of synoptic variability of the mentioned parameters at each considered HMS estimates of their average daily values from 1977 to 2005 were obtained. For the temporal water temperature series we carried out the high-frequency filtering including the removal of seasonal and interannual variations caused primarily by the annual cycle of sea water heating/cooling by moving averaging with 45 day rectangular window. In this paper we consider the synoptic water temperature anomalies (SWTA) with respect to its seasonal trend (Fig. 2).

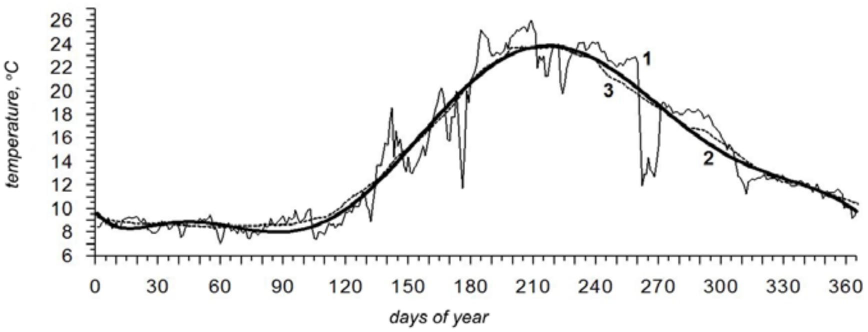

Fig. 2. Scheme of SWTA extraction (°C): *1* – curve of mean daily values; *2* – 8th order polynomial trend; *3* – 45 day moving average values at Sochi HMS in 1987

In all the aforementioned HMS for each day of the long-time average annual year the RMS and average SWTA values were obtained, that were subjected to statistical analysis – i. e. evaluations of statistical moments, trends, their reliability degree, the mutual regression relations under the characteristic intra-annual periods.

Results and their discussion. Before starting the analysis of the results, we should note that SWTA in the surface layer of the coastal zone due to the complex, interrelated factors [23], such as: synoptic variations in wind speed and direction respectfully to the shore, favoring either upwelling or downwelling; thickness of the upper mixed layer (UML) and the value of the vertical temperature gradient in the underlying layer (in spring, summer and autumn – in the seasonal thermocline, in the winter – in the main pycnocline); synoptic reinforcements of the autumn-winter cooling of the sea and the variability of heat transfer by currents. Synoptic wind anomalies are proportional to the wind effect intensity of and sea heat irradiation, the vertical temperature gradient in the thermocline and inversely proportional to its occurrence depth and UML thickness.

Analysis of the results of monitoring data processing permits to suggest the existence of 5 consequent (seasonal) variability modes of the RMS (1977 – 2005) SWTA values during the year in all the areas of the HMS considered (Fig. 3). Meanwhile the features of each of the mentioned seasonal modes (medium level of the SWTA values, the sign and swing of the linear trend, dispersion deviations with respect to the trend) at all the HMS are similar.

In addition, timing and duration of these periods are sufficiently close. All this testifies the unity of the processes determining SWTA in the north-eastern part of the Black Sea. The exception is that the most northern one of the areas under consideration – the Anapa HMS, due to significant difference from its natural environment – the wider shelf and significant influence of the continental atmospheric processes in comparison with the rest of the HMS, closed from the north-east by the Great Caucasus Range.

Description of the modes we are to explain by giving an example of Tuapse HMS, psituated in the middle of steep area of the Black Sea coastal zone. In Fig. 4 the long-time average annual variation of the SWTA RMS values (Fig. 4, *a*) is combined with seasonal long-term distribution of the separate SWTA at Tuapse HMS, averaged over a 10-day interval to reduce the number of small parts of the field (Fig. 4, *b*).

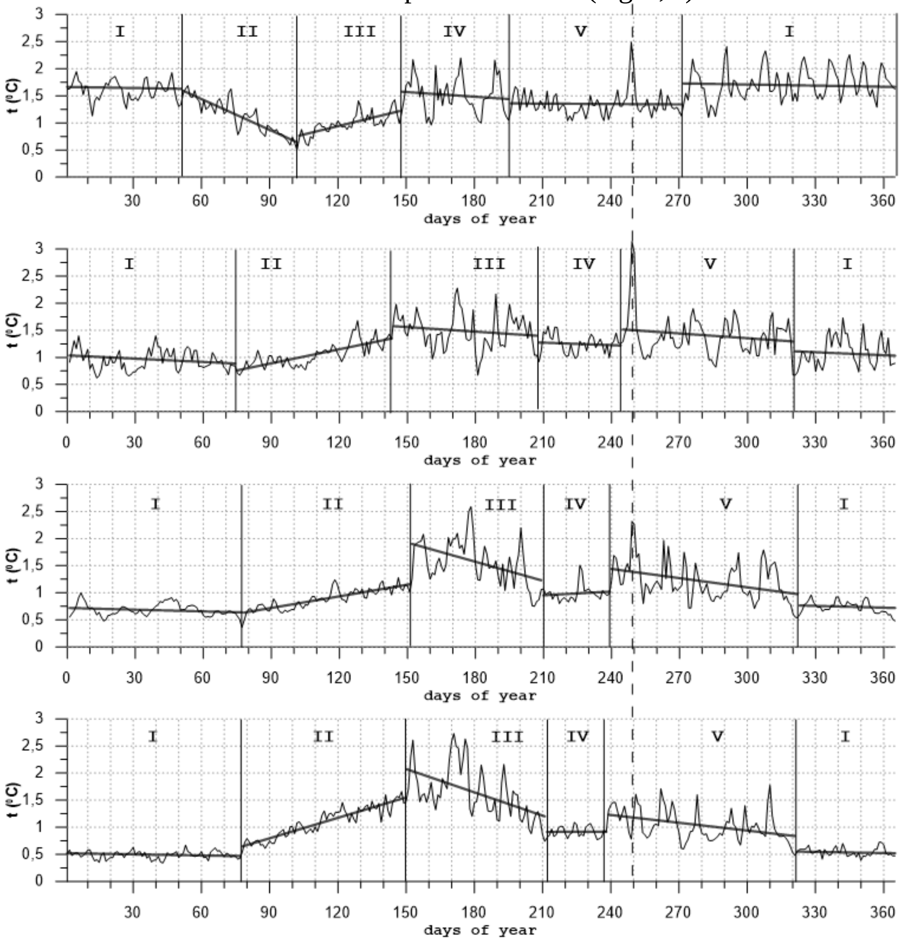

Fig. 3. Intra-annual variability of SWTA RMS (°C) under data of the HMS situated off the northeastern Black Sea coast (from top to bottom): Anapa, Gelendzhik, Tuapse and Sochi. Roman numerals indicate the modes with the different nature of intra-variability

The first of the modes under consideration (I) falls on the period from late autumn to early spring and has the longest duration – about 120 days. Fig. 3 shows, it is characterized by a minimum average levels of the SWTA RMS values (except, as has already been noted, the Anapa HMS). The reason for such low values is the large thickness due to the convective agitation, and hence the inertia of the autumn and winter UML in the Black Sea (up to 50 – 60 m) underlying at the bottom by the layer of the main pycnocline with small vertical temperature gradients [24]. The number of the significant SWTA (more than 1°C under the absolute value) at this period is small. Almost all of them have negative sign (Fig. 4, *b*) and are connected with the synoptic intensifications of the sea heat irradiation during the intrusions of cold air masses from the Eastern European subcontinent. The swing of the SWTA linear trends in summer – winter is close to zero at all the HMS. Discreteness of the deviations with respect to the trend significantly increases from the south to north (from 0.07 to 5.80°C^2, see the table), which is associated with sublatitudinal intensification of autumn and winter wind activity and radiation cooling, determining the agitation processes in the surface layer of the Black Sea.

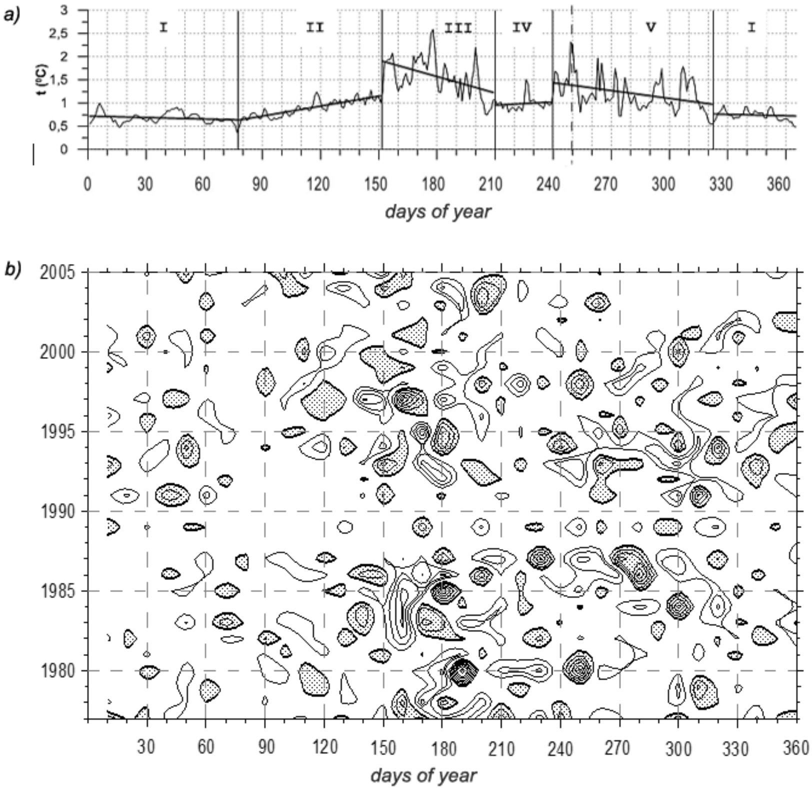

Fig. 4. Long-time average annual variation of the SWTA RMS values *(a)* seasonal long-term distribution of the separate SWTA at the Tuapse HMS. Discreteness of the isolines is 0.5 °C, the negative values are shaded

The mode of SWTA spring increase (II) starts in the second half of March and lasts till the end of May. Its average duration is about 70 days (in Anapa area – 50 days). Swing of the SWTA linear trends exceeds 0.5 °C. The discreteness of the deviations respectfully to the trend in the spring decreases by 0.5 – 1.5 °C 2 (see table). This SWTA behavior in this period can be explained by the heating of the sea water surface layer and, consequently, the emergence and development of the near-surface seasonal thermocline. The shallow depth and low inertia of the UML, as well as the growth of vertical temperature gradients in the seasonal thermocline in spring lead to an increase in the significant SWTA repeatability (including the positive ones, see Fig. 4), despite the weakening of the spring wind activity.

In summer, there are two types of synoptic variability of surface water temperature anomalies. One of them (III) can be called "upwelling" mode, the other shorter (IV) – "thermal stabilization" mode.

"Upwelling" mode is characterized by the highest average level of the SWTA values (see Table) and their pronounced local maxima (Fig. 3) with one or two-week intermittency, increasing from the north to south. In the same direction, the negative slopes of the SWTA linear trends and variance of deviations from them that reflect the process of the UML thickness and heat irradiation, increase due to wind and wave agitation under the sea warming intensity weakening in summer.

However, in early summer (i. e. during the first half of the mode III) the UML thickness is not too high, so the ascending vertical water movement during the upwelling almost always leads to colder deep water release to the Black Sea surface. Such occurrences manifest themselves in the form of large negative anomalies of mean daily water temperatures, i. e. SWTA, which considerably prevail at that moment by repeatability and magnitude over the positive anomalies (Fig. 4, *b*). This is also evidenced by the statistically accurate negative correlation (with a coefficient of 0.78) between the sign and magnitude of SWTA in Fig. 5, *a*, showing the correspondence of the SWTA RMS with the daily averaging for mode III in the Tuapse HMS.

Statistical characteristics of the SWTA RMS in the various year periods according to HMS data in the northeastern part of the Black Sea

Statistical parameters of SWTA variability	Mode No.				
	I	II	III	IV	V
Anapa HMS					
RMS value, °C	1.68	1.12	0.99	1.51	1.35
Linear trend discreteness, °C^2	0.12	3.97	0.80	0.08	< 0.01
Discreteness of deviations respectfully to the trend, °C^2	9.55	1.00	0.75	5.12	3.86
Gelendzhik HMS					
RMS value, °C	1.01	1.06	1.49	1.25	1.41
Linear trend discreteness, °C^2	0.48	2.04	0.17	0.01	0.32
Discreteness of deviations respectfully to the trend, °C^2	5.80	1.34	6.62	1.03	11.07
Tuapse HMS					
RMS value, °C	0.70	0.90	1.57	0.99	1.21
Linear trend discreteness, °C^2	0.16	1.73	2.26	0.01	1.53
Discreteness of deviations respectfully to the trend, °C^2	1.45	0.64	7.40	0.62	9.23
Sochi HMS					
RMS value, °C	0.51	1.09	1.64	0.91	1.04
Linear trend discreteness, °C^2	0.07	4.92	4.08	0.00	1.10
Discreteness of deviations respectfully to the trend, °C^2	0.64	0.84	10.00	0.24	5.50

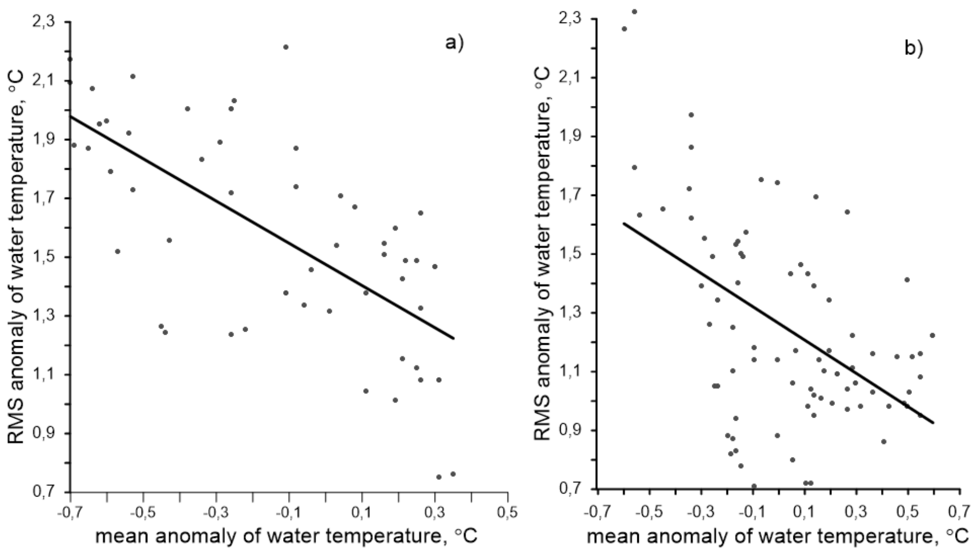

Fig. 5. Conformity diagrams and linear regression line of arithmetic and SWTA RMS values according to the Tuapse HMS data: *a* – mode III, *b* – mode V

The other SWTA generation mechanisms (wind-wave turbulent entrainment in UML of the underlying thermocline waters, synoptic water heating/cooling through the sea surface, heat advection) during the mode III are ineffective because of the weakness of local winds and the spatio-temporal homogeneity of background surface thermal conditions (spring-summer sea surface warming).

"Thermal stabilization" mode (IV) falls on August and is the shortest. At this time the summer UML, having the highest heat irradiation, reaches its maximum thickness, due to wind and wave agitation, whereby the underlying cold water thermocline rarely reaches the sea surface, even at significant synoptic upwelling. As a result, the efficiency of this SWTA generation mechanism in August considerably drops, which manifests itself in the following statistics: repeatability of significant SWTA sharply decreases (Fig. 4, *b*), the average levels their RMS value decrease by 1 °C (Fig. 3), the trends of anomalies are almost absent, and discreteness of the deviations relatively to the average level do not exceed 1 $°C^2$ (see Table).

Along with the beginning of autumn sea water cooling, the mode (V), called "convective-upwelling", starts. The main factor of the SWTA formation at this period is a synoptic intermittence of the sea water cooling intensity. However, under the autumn synoptic intrusions of cold air masses the formation of large negative SWTA occurs not only due to the sea UML heat irradiation through its surface, but also due to the convective entrainment of colder underlying thermocline waters in it. Such entrainment is much more effective than summer wind-wave one (mode III). It many times strengthens under upwelling of the thermocline waters. In the synoptic intervals between such events the sea water convective cooling can be completely suppressed by downwelling, which leads to significant positive SWTA. Thus, the autumn upwelling/downwelling considerably modulates the process of seasonal sea water cooling, which is clearly seen in Fig. 2

and 4 in the increase of the repeatability and magnitude of significant SWTA. Negative SWTA in this period prevails by the magnitude (Fig. 5, *b*), while the corresponding correlation coefficient is slightly lower (0.65) than in the early summer, and the SWTA repeatability of the both signs is almost the same.

The average duration of the mode V is 80 days. As in the mode III, at the beginning of summer the average level of SWTA RMS values significantly increases (Fig. 3), negative trends appear again (as a result of the UML thickness increase), but the discreteness of deviations from them are growing from the south to north – from 5.5°C^2 near Sochi to 11.1°C^2 in Gelendzhik area – along with the cooling velocity increase (see table).

As it has already been noted before, the Anapa area is different from the areas of the other HMS by mismatch of characters, phases and duration of the SWTA modes described above. The autumn-winter mode I differs here by longer duration (140 days), increased level of the SWTA RMS and discreteness (see Table). Such differences in SWTA properties are caused by the shallow water areas of the Anapa HMS area and consequently by the least thermal inertia of its waters, as well as by the greater intensity of synoptic weather effects (momentum and heat fluxes through the sea surface).

Mode II is unique for the area of Anapa. Due to the sharp reduction of wind activity in mid February [25, 26] the process of vertical agitation reduces, significantly affecting SWTA, which decrease during this period (50 days) more than twice.

Modes III and IV near the Anapa HMS are completely similar to modes II and III, respectively, in the other examined regions. Similar SWTA variability parameters (see Table), and the proximity of the transition period of the specified modes at the Anapa HMS and the rest of HMS show common processes throughout the considered area in this period.

Mode V at the Anapa HMS under its properties is similar to mode IV in the remaining HMS. However, its duration is 2 – 3 times more, and it goes directly into the autumn-winter mode I. Thus, there is no "convective-upwelling" mode, observed at the HMS with steep coast from early September to mid November, monitored in the shallow water area of Anapa. It confirms the important role of the convection-turbulent entrainment of cold water at the UML bottom border and its upwelling intensification in the formation of this mode, as these factors are not active in the area of Anapa. At this period only synoptic intensification and heat irradiation weakening from the sea surface, not sufficient for the formation of large SWTA, are active here [27].

Conclusion. Firstly performed the annual cycle analysis of variability of long-term SWTA RMS values with daily discreetness according to the nearly 30-year observations at the HMS in the northeastern part of the Black Sea draws us to the following conclusions.

1. Five modes of the SWTA variability are revealed, their beginning phases and parameters are close to the steep coast HMS (Sochi, Tuapse and Gelendzhik), but the Anapa HMS has significant differences in autumn-winter period. The sharp transitions between the modes should be noted.

2. Each mode is characterized by a complex of interacting thermal and dynamic processes. It is shown that in June – July (Mode III) and in September – November (Mode

V) thermal effects of coastal upwelling prevail, providing maximum SWTA (at daily averaging up to 9 – 10 °C). In summer the sea water temperature synoptic variability increases significantly from the north to south, in winter – from the south to north.

3. High repeatability and value of SWTA determine their climatic and operative (synoptic) significance in the formation of the anomalies of the marine environmental conditions in the northeastern part of the Black Sea coastal zone. In this regard, the need for operative and climate monitoring, as well as further research of their formation mechanisms and environmental consequences are obvious.

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