Investigation of the spatio-temporal variability of the Black Sea upper mixed layer thickness based on the results of numerical calculations

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Abstract. The results of the Black Sea uniform mixed layer (UML) thickness determination were used for investigation of its spatio-temporal variability based on numerical calculations of the monitoring and forecasting center of the Black Sea (BS MFC). The spatial distribution of the mean and standard deviations of the UML depths in the Black Sea has been studied over the seven-year period. The time series analysis of UML thickness was performed by their spatial averaging over the Black Sea area for each day of the seven-year period. The principal components of the variability of the spatio-temporal UML depths field have been studied. The areas of high and low UML depths variability and the frequency-time characteristics of their variations have been determined.

1. Introduction
Investigations of the spatio-temporal variability of the Black Sea UML thickness under the influence of changes in the heat, evaporation, precipitation and components of wind stress fluxes in the atmospheric boundary layer are of interest in terms of processes occurring at the boundary of two media as well as for analysis and forecasts. There are many works [1, 2] that attempt to solve this problem. Nevertheless, these results require further clarification and verification. The UML often refers to the upper isothermal layer of the sea. It is this UML definition that is used in this paper.

The aim of this work is to assess the spatio-temporal variability of the Black Sea UML depths by using the model calculations of the seawater temperature. The study is based on the joint use of the multivariate statistics, classical spectral methods and nonstationary signals analyzing method that is based on Empirical Mode Decomposition (EMD) [3].

2. Data used
Large arrays of circulation models calculations and in situ data measurements of seawater temperature have been accumulated for the Black Sea [4]. The automatic operational system of Black Sea state analysis and forecast is running in the Monitoring and Forecasting Center of the Black Sea (BS MFC) [5]. The model calculations using this system were used to solve this task from 2012 to 2018. In general, 2557 daily averaged three-dimensional fields of seawater temperature were used for UML depth calculations by using algorithm that was developed in [6] and adapted in [7] for the Black Sea water area.
3. Investigation of the mean UML thickness

The map of the spatial distribution of the mean UML thickness is shown in figure 1 (a). We can see that the highest UML depths are observed in the western part of the deep-water region of the Black Sea, in the lowest in the southeast part.

![Figure 1](image.png)

**Figure 1.** Maps of the means (a) and standard deviations (b) of the UML thickness.

The map of the spatial distribution of standard deviations of the UML thickness is shown in figure 1b. The gray-scale palette displays the UML depths varying from 0 to 10 m. Values greater than 10 m are displayed in white. There are several areas with high variability of the UML depths – from 12 to 14 m. They are located near the coast between Sinope and Trabzon, between Anapa and Tuapse, between Feodosia and Evpatoria. The area with a center in 40 °E, 42.3 °N is located in the southeastern region of the Black Sea. There is a low variation in the UML depths. It is seen in figure 1 (a) though less clearly.

The time series of the UML depths - \( H_{\text{UML}}(t) \) obtained by their spatial averaging over the Black Sea for each day of the seven-year period is shown in figure 2. Strong variations in the UML thickness with respect to the seasonal component are a distinctive feature of this time series. The highest depths vary from year to year, indicating nonstationarity of this time series.

![Figure 2](image.png)

**Figure 2.** Time series of the daily mean values of UML thickness.

A number of new approaches to the study of non-stationary processes have been developed over the past three decades, including the Empirical Mode Decomposition (EMD) [3]. As a result of its implementation, the initial non-stationary time series is represented as the exact amount of Intrinsic Mode Functions - \( IMF_i(t) \), and the residual – \( Res(t) \). Modes \( IMF_i(t) \) are sinusoidal analytical signals with amplitude-frequency modulation. Due to this, instantaneous amplitudes and frequencies can be calculated for each mode and the Hilbert Spectrum of the original signal can be obtained. Function \( Res(t) \) has a smooth, aperiodic variation and is not used for estimation of spectral characteristics. Currently, this method continues to develop intensively and the corresponding results are presented in [8] etc.

An example of EMD implementation for the studied time series of \( H_{\text{UML}}(t) \) values is shown in figure 3 and table 1.
Table 1. Statistical characteristics of the instantaneous frequencies and amplitudes of the intrinsic mode functions.

| Parameter | \( IMF_1 \) | \( IMF_2 \) | \( IMF_3 \) | \( IMF_4 \) | \( IMF_5 \) | \( IMF_6 \) | \( IMF_7 \) |
|-----------|------------|------------|------------|------------|------------|------------|------------|
| \( Med_f \) (1/day) | 0.21 | 0.11 | 0.058 | 0.031 | 0.017 | 0.0027 | 0.0012 |
| \( Mad_f \) (1/day) | 0.13 | 0.044 | 0.019 | 0.009 | 0.0048 | 0.00081 | 0.00021 |
| \( T \) (day) | 4.69 | 8.84 | 17.3 | 32.4 | 59.4 | 372 | 857 |
| \( Med_A \) (m) | 0.57 | 0.79 | 1 | 0.77 | 0.85 | 8.3 | 0.36 |
| \( Mad_A \) (m) | 0.48 | 0.69 | 0.71 | 0.76 | 0.61 | 1.6 | 0.29 |

The studied time series can be represented by the sum of the seven functions \( IMF_i(t) \) and the residual – \( Res(t) \). The median estimates of the average frequency of the modes \( Med_f \) are given in table 1. They decrease as the number \( IMF_i(t) \) increases. The median estimates of the mode frequency standard deviation – \( Mad_f \) vary in a similar way. The ratio of the standard deviation of the mode frequency to the mean frequency decreases with increasing mode number. This suggests that the intensity of the frequency modulation \( IMF_i(t) \) is reduced with a decrease in the mean frequency.

The first four synoptic modes with average periods \( T = 1/Med_f \) varying from 5 to 30 days are sequences of wave packets. The number of wave packets per year, their time localization, instantaneous frequencies and amplitudes have an irregular pattern of variability which confirms the non-stationary variability of \( H_{ULM}(t) \). The wave packets are more diffuse and have less regular shape in the fifth seasonal mode, which has the period of about 2 months. The sixth seasonal mode has a period of 372 days, that is, it is a one-year mode of fluctuations of the UML thickness. It varies very smoothly, has an almost constant and significantly higher mean amplitude compared to the mean amplitudes of other modes.

The mean amplitudes of the first five modes vary in the range from 0.57 to 1 meter. The standard deviations of the amplitudes of the first five modes – \( Mad_A \) vary from 0.48 to 0.76 m. The mean amplitude of the sixth annual mode is approximately 8 meters, and the standard deviation is 1.6 m. The latest mode has the form of damped oscillations with a period of about two and a half years. Its mean amplitude and standard deviation of the amplitude is significantly less than that of other modes. The residual is an aperiodic function, smoothly varying from 10 to 13.5 meters. At the same time, from 2012 to beginning of 2017, it has the shape close to a cubic parabola and then almost does not change taking a value approximately equal to 12.5 m.

The use of classical spectral methods with high resolution in frequency and low accuracy of spectrum estimation allows identifying weak energy peaks at frequencies corresponding to periods of 90, 120 days and a strong peak corresponding to a period of one year. It is possible to identify weak spectral peaks at frequencies corresponding to periods from 2 to 10 days when we decrease the spectral resolution and increase the accuracy of the spectrum estimate.

4. Investigation of the principal components of UML thickness

Investigation of the oceans and atmosphere physical fields by using Principal Component Analysis has a long history [9]. In the present work, we use a representation where temporal principal components (TPC) are renormalized in such a way that their values vary in the range from -1 to 1. The energy-consistent renormalization of the spatial principal components (SPC) is performed in such a way that they vary in the range of the natural variability of the UML depths.
Figure 3. Intrinsic mode functions and residual of the $H_{UML}(t)$. 
Figure 4. Principal components (PC) of the UML thickness: (a) PC relative cumulative energy; (b)-(d) – 1–3 spatial principal components (m); (e)-(h) – 1–4 temporal principal components.

Cumulative relative energy of PCs is shown in figure 4 (a). The sum of the first three PCs contains 70% variance of the UML thickness variability. The first three SPCs are shown in figure 4 (b-d). White lines separate the areas of positive and negative SPC values. The sum of the first and third SPCs has a high degree of similarity with the standard deviations of the UML depths at different points of the Black Sea area which are estimated according to all 2557 calculations related to different moments of time. Fragmentation of the Black Sea area into intermittent small areas of positive and negative SPC values increases in higher order modes. The first TPC is shown in figure 4 (e), and it is similar to a time series of UML thickness averaged over the Black Sea area. The second, third, and fourth TPCs are shown in
figure 4 (f-h). Their main feature is in the highly irregular variability of TPCs values. Smooth seasonal and inter-annual variability can be recognized as well. With increasing PC numbers, the corresponding TPCs take the form of sequences of irregular wave packets with localization mainly in the fourth and first quarters of the two adjacent years. Seasonal and inter-annual variability fade away. Intrinsic mode functions, mean and standard deviations of the instantaneous frequencies and amplitudes $IMF_{0}(t)$ of the first TPC are qualitatively similar to those of a time series of mean UML depths. This analogy also holds for higher-order TPCs with the exception of the interannual, annual, and seasonal components $IMF_{j}(t)$. Their amplitudes are significantly reduced compared to amplitudes of IMF mean UML depths.

Conclusions
The spatial distribution of the Black Sea UML thickness obtained for seven-year period is characterized by the greatest thicknesses in the western part of the deep-water basin where it reaches 12 m. Several areas with increased variability of the UML depths are distinguished in the spatial distribution of standard deviations of the depths (up to 12-14 m). They are located near the coast between Sinop and Trabzon, between Anapa and Tuapse, between Feodosia and Evpatoria. The region with a lower UML depth variation is located in the southeastern region of the Black Sea. The synoptic-scale processes at frequencies corresponding to periods of 4-5, 8-10, 13-17, 27-35 days, seasonal scales processes corresponding to periods of 55-75 and 355-375 days and damped interannual variability at frequencies corresponding to a period of about 2.5 years are observed in the time series of mean values and main components according to the results of the temporal variability analysis using the EMD method.

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