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Specific Features of Heat Exchange between the Black Sea and the Atmosphere in Winter in 1971–1991

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Abstract—The reanalysis of three-dimensional fields of water temperature and velocity of currents in the Black Sea in January–March in 1971–1991 is used for studying the spatial distribution of sea surface temperature, heat content of the upper layer, and heat fluxes on the sea surface near the Caucasian coast and the southern coast of Crimea. It is demonstrated that a warm current in the upper layer of the sea and the high values of the heat flux from the sea to the atmosphere are observed in these areas in winter. The possible effect of the above features on the interannual variability of winter air temperature in Sochi and Yalta is assessed.

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1. INTRODUCTION

The creation of operational systems for the diagnosis and forecasting of the state of seas and oceans based on the use of numerical models of ocean circulation with the assimilation of all available observational data on marine environmental conditions was the culmination of the development of methods of operational oceanography [9]. In 2008–2014 such system was developed for the Black Sea as an element of the prototype of the pan-European marine forecasting service in the framework of projects “MyOcean” and “MyOcean2” of the EU Seventh Framework Programme. It is maintained by the Black Sea Marine Forecasting Center currently operating in the autonomous mode at the Marine Hydrophysical Institute (MHI) of Russian Academy of Sciences [8]. One of the products of the Black Sea Marine Forecasting Center is the retrospective analysis (reanalysis) of circulation and thermohaline fields of the Black Sea for the period of 1971–1991. The description of the Black Sea circulation model and assimilation algorithm used for computations is presented in [7, 10].

The fields of temperature and velocity of currents obtained in the process of reanalysis have a high spatial and temporal resolution. Using such dataset, it is possible to study the specific features of heat exchange between the Black Sea and the atmosphere in the eastern part of the basin in winter and to discuss its effects on the climate of the Caucasian and Crimean coasts.

The first studies of seasonal variations in sea water temperature retrieved by the assimilation of long-term hydrological datasets in the Black Sea circulation model demonstrated that a warm current related to the advective transport of water with the Black Sea Rim Current is observed near the Caucasian coast [14] and the southern coast of Crimea [3] in winter. Then papers [1, 2, 5, 11] noted that a tongue of warm water stretched along the Black Sea Rim Current exists close to the southern coast of Crimea. This conclusion was based on the analysis of sea surface temperature (SST) from in situ and satellite data. In the south, this area is separated from the cold water of the central part of the sea by the clearly pronounced front characterized by the negative values of meridional temperature gradients [1].

The above features of water temperature field both on the sea surface and in the upper water layer are also manifested in the reanalysis data. The objective of the present paper is to analyze the fields of SST and heat content of the active sea layer and the spatial distribution of heat fluxes in the eastern part of the Black Sea. We also aim to assess the possible effects of the warm current on the climate softening in the area of the Caucasian coast and the southern coast of Crimea.

2. DATA AND METHODS

The present study is based on reanalysis data on temperature and velocity of currents in the Black Sea in 1971–1991. The horizontal resolution of the data is 5 5 km, the vertical resolution varies from 2.5 to 12.5 m in the upper 100-meter layer of the sea, and the time step is 1 day.

The reanalysis data on SST were used for studying its spatial distribution along the Caucasian coast and the southern coast of Crimea (sea areas 1 and 2 in Fig. 2 below). The values of the Black Sea heat content were additionally computed from the water temperature fields at 10 depths in the layer of 0–62.5 m. The analysis of the spatial distribution of heat content was used for corroborating the specific features of distribution of SST and heat exchange between the Black Sea and the atmosphere in winter which are related to the presence of warm water on the sea surface near the Caucasian coast and the southern coast of Crimea.

To investigate the spatiotemporal features of heat exchange between the Black Sea and the atmosphere, heat fluxes were computed by the heat budget method using the fields of water temperature and velocity of currents. The heat fluxes calculated for every year were averaged within every winter month and were compared with the data of previous studies [4] and with the data on heat fluxes from [13] averaged for a month.

To assess the interrelation between the processes of heat exchange intensification and the climate of the Caucasian coast and the southern coast of Crimea, information on monthly mean values of air temperature at Yalta (the data were obtained during joint studies with the Hydrometeorological Service of Ukraine in 1996–2002) and Sochi weather stations [12] in February was additionally used as well as data on heat fluxes from the ERA-40 dataset. These data were used for analyzing the linear regression dependence between air temperature and heat fluxes in the local areas of the Black Sea under study. For this purpose, data on monthly mean heat fluxes obtained by the heat budget method were averaged for two areas under study. The ERA-40 data were averaged for February of every year in 1971–1991 and for the whole Black Sea area.

3. RESULTS AND DISCUSSION

3.1. Spatial Distribution of SST and Heat Content of the Upper Sea Layer

The spatial distribution of SST in winter in 1971–1991 based on the reanalysis data has a typical pattern. Figures 1a, 1c, and 1e present the examples of the fields of deviation of water temperature from its mean values computed for the sea area for January 16, February 14, and March 16, 1977, respectively. It is clear that the tongue of warm water with the maximum deviation from the average temperature (calculated for the Black Sea area) equal to 0.5–0.7 C is observed near the southern coast of Crimea. Such SST anomalies in winter are observed in all years and on all days of this season. The tongue of warm water near the Caucasian coast and southern coast of Crimea is observed within the whole water layer from 0 to 62.5 m that is indicated in the spatial distribution of heat content anomalies. The examples of the spatial pattern of the Black Sea heat content anomalies for the sea area where the depth exceeds 62.5 m, are also presented for the winter of 1977 in Figs. 1b, 1d, and 1f. The comparison of the fields of heat content anomalies with the respective SST fields reveals that they are characterized by a similar spatial pattern.

As clear from Fig. 1, the source of warm waters transported with the Black Sea Rim Current along the Caucasian coast and the southern coast of Crimea is the southeastern part of the Black Sea. In this part of the sea a positive anomaly of water temperature occupying the significant area is formed from the surface to the depth of several tens of meters in autumn.

The accumulation of warm water in the southeastern part of the basin is schematically explained by the changes in the Black Sea Rim Current regime in autumn. In autumn the Black Sea surface temperature becomes higher than air temperature. The local heating of the atmosphere leads to the development of a local cyclone over the sea [6] which induces the field of sea surface drag that has cyclonic vorticity. Such sea surface drag causes the water rise on the lower boundary of the Ekman's friction layer and, hence, the movement of warm water heated during summer towards the shore and the intensification of the Black Sea Rim Current. The analysis of water temperature distribution at different depths in autumn reveals that the most intense accumulation of warm water occurs along the northern and northwestern boundaries of the Black Sea. Then warm waters are transported by the current along the coast and are accumulated in the southeastern areas under the influence of the Batumi anticyclone. The positive anomaly of SST in the southeastern

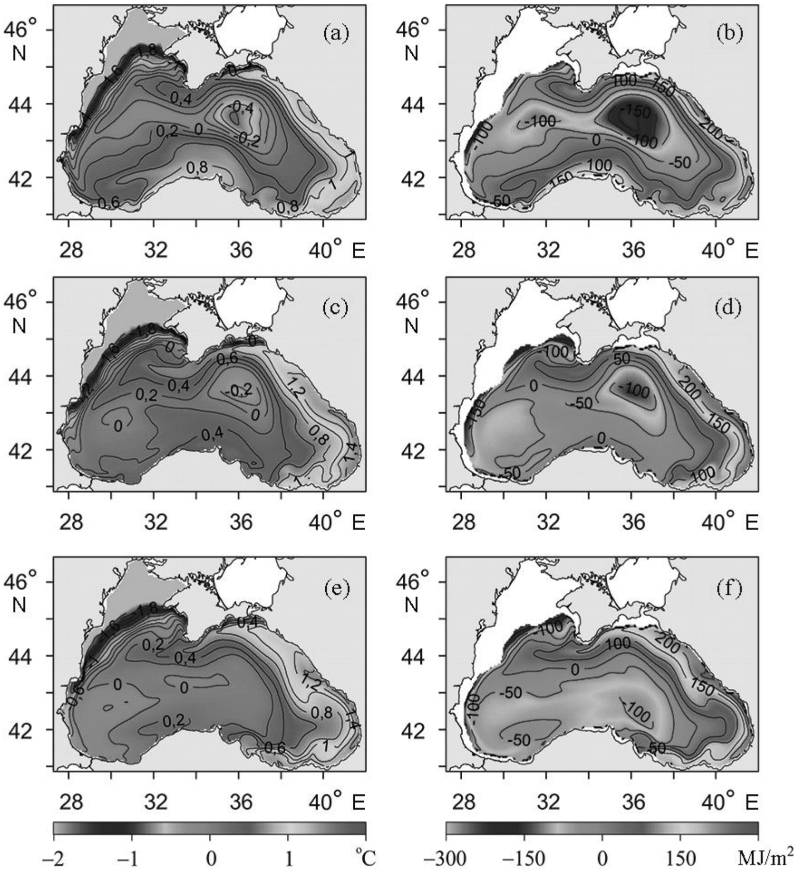

Fig. 1. The anomalies of (a, c, e) sea surface temperature and (b, d, f) heat content of the Black Sea in the layer of 0–62.5 m relative to the sea-averaged values on (a, b) January 16, (c, d) February 14, and (e, f) March 16, 1977. The article with colored figures is available at the site http://link.springer.com.

part of the Black Sea is maintained for a certain period of time due to the relatively less intensive cooling in this area. After that excessively warm waters are partially captured by the Black Sea Rim Current in the middle and end of autumn and are transported along the coasts of the Caucasus and Crimea. The process of warm water transport from the southeastern part of the sea along the coasts of the Caucasus and Crimea lasts till the end of March–the beginning of April, when the next cycle starts of the Black Sea heating and Black Sea Rim Current weakening.

3.2. Analysis of Spatiotemporal Variability of Heat Fluxes from the Black Sea to the Atmosphere in Winter in 1971–1991

Heat fluxes on the sea–air interface were calculated from the heat budget equation for the liquid column:

$$_{\mathrm{S}} \qquad _{u} \qquad _{v} \qquad _{\mathrm{Th}} \qquad _{\mathrm{H}} \qquad _{\mathrm{BH}} \qquad _{\mathrm{a}} \tag{1}$$

where $_{\mathrm{S}}$ is the variation in the heat content of the water column with the specified horizontal section from the sea surface to the depth of 62.5 m; $_{u}$ and $_{v}$ are the zonal and meridional components of advective heat flux divergence for the separated water volume, respectively; $_{\mathrm{Th}}$ is the integral horizontal turbulent heat flux; $_{\mathrm{H}}$ is the sum of convective and vertical turbulent heat fluxes for the separated water volume at the depth of 62.5 m; $_{\mathrm{BH}}$ is the flux of shortwave photosynthetically active radiation at the depth of 62.5 m or at the sea bottom, if the depth is less than 62.5 m; $_{\mathrm{a}}$ is the total turbulent and radiative heat flux from the sea to the atmosphere. The value of $_{\mathrm{a}}$ can be determined from (1) taking into account the values of $_{\mathrm{S}}$, $_{u}$, $_{v}$, $_{\mathrm{Th}}$, $_{\mathrm{H}}$, and $_{\mathrm{BH}}$. All parameters were determined so that the flux $_{\mathrm{a}}$ was positive when the heat comes from the atmosphere to the sea, and negative in the opposite case.

The fluxes of $_{\mathrm{S}}$, $_{u}$, and $_{v}$ were calculated from the reanalysis data on temperature and velocity of currents in each vertical box with the base of 5 5 km and with the height of 62.5 m. The additional assumptions were made for estimating the remaining three parameters needed to compute $_{\mathrm{a}}$.

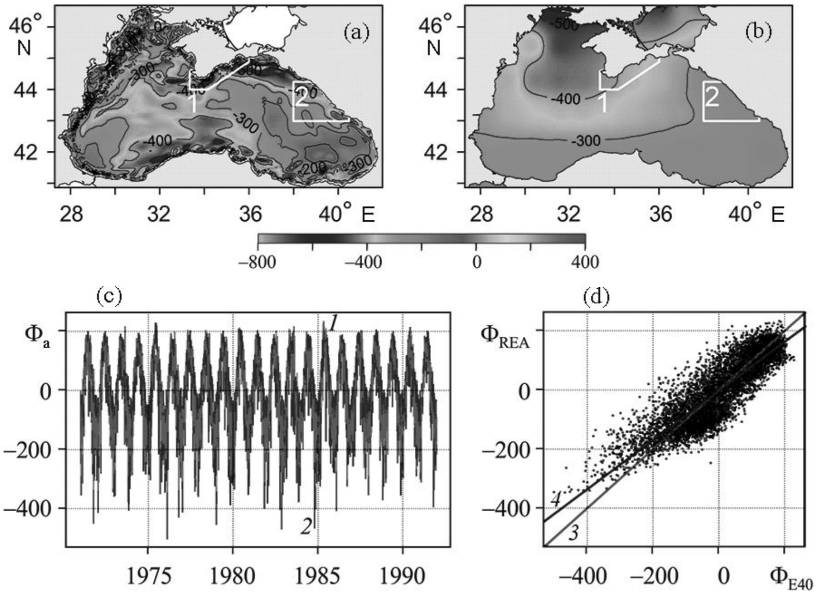

Fig. 2. The heat flux from the Black Sea to the atmosphere (MJ/(m^2 month)) in February 1985 from the data of (a) marine reanalysis and (b) ERA-40 reanalysis; (c) the time series of monthly mean values of the heat flux averaged over the Black Sea area according to the data of (*1*) marine reanalysis and (*2*) ERA-40 atmospheric reanalysis; (d) the two-dimensional distribution of heat fluxes $_{\text{REA}}$ and $_{\text{E40}}$. In figures a and b: 1 is the area of the southern coast of Crimea; 2 is the area of the Caucasian coast; in figure d: (*3*) the isoline of values of $_{\text{REA}}$ and $_{\text{E40}}$; (*4*) the regression $_{\text{REA}}(\ _{\text{E40}})$.

It was assumed that $_{\text{BH}}$ 0 for the depth of 10 m and more in the coastal areas and in the sea areas where the depth exceeds 50 m. The contribution of integral horizontal and vertical turbulent fluxes $_{\text{Th}}$ and $_{\text{H}}$ could be computed from the reanalysis data. However, according to the estimates of these parameters presented in [4], they contribute insignificantly to the heat flux from the sea to the atmosphere; therefore, they were neglected in the present calculation of sea–air heat exchange. After computing $_{\text{a}}$ for each separate box, these values were normalized to its base area.

Based on the computation of the daily fields of the heat flux from the sea to the atmosphere, monthly mean values for January, February, and March of every year were calculated. An example of the monthly mean heat flux from the sea to the atmosphere $_{\text{a}}$ for February 1985 (one of the most severe winters in 1971–1991) is presented in Fig. 2a. It is clear that the zones of $_{\text{a}}$ high values are observed near the Caucasian coast and the southern coast of Crimea. In January similar features are registered for monthly mean fields, and the intensity of heat exchange is slightly higher than in February. In March heat fluxes from the sea to the atmosphere are smaller than in February. In some years there were situations when heat came from the atmosphere to the sea near the southern coast of Crimea. Nevertheless, the high values of the heat flux from the sea to the atmosphere are observed in the eastern and northeastern parts of the sea in the coldest winters and in 1971–1991 on average.

Thus, the analysis of variability of the heat flux from the sea to the atmosphere near the Caucasian coast and the southern coast of Crimea reveals high heat emission from the sea in winter.

3.3. Analysis of Relationship between Air Temperature and Heat Fluxes from the Sea to the Atmosphere

As the above zone of high heat emission is located close to the part of the Black Sea coast with subtropical climate, it is interesting to estimate quantitatively the impact of the Black Sea Rim Current warm water on the variations in winter air temperature near the Caucasian coast and the southern coast of Crimea. For this purpose, let us analyze how monthly mean values of air temperature T_a calculated from the results of continuous observations at two weather stations in Yalta and Sochi in February in 1971–1991 depend on the heat flux from the sea to the atmosphere.

First of all, it should be noted that the Black Sea heats the local atmosphere in winter. The interannual variability of the heat flux from the sea to the atmosphere as well as of air temperature on the sea coast is driven by global atmospheric processes, for example, by the invasions of cold air masses. Therefore, the mean heat flux from the sea to the atmosphere averaged for the sea surface may be an indicator of contribution of global atmospheric processes to air temperature variability in Yalta and Sochi. There is a heat flux from the sea to the atmosphere in the part of the Black Sea Rim Current that adjoins the Caucasian coast and the southern coast of Crimea; let us choose it as the other indicator characterizing the local effects of warm waters on air temperature variations in this area in winter.

In accordance with the above, let us consider two time series for studying the relationship between air temperature and the heat flux. The first time series $_{\mathrm{REA}}$ is formed of monthly mean values of heat flux $_{\mathrm{a}}$ which are calculated from (1) and averaged over one of the areas under study (1 or 2, Fig. 2a). This time series contains the most precise information on the spatial features of the heat flux in these areas. The problem of construction of the series of heat fluxes averaged over the sea surface is more difficult. The insufficient volume of in situ observations assimilated during the reanalysis of water temperature and velocity of currents in the Black Sea for the period of 1971–1991 should result in the higher temporal smoothness of heat fluxes estimated from (1). Figures 2c and 2d present the comparison of time series of average daily and monthly mean heat fluxes from the Black Sea to the atmosphere averaged throughout the sea surface for the period of 1971–1991 and obtained from the data of MHI marine reanalysis and ERA-40 atmospheric reanalysis. It is demonstrated that both time series indicate the typical features of variations in global heat fluxes. However, the variations obtained from the marine reanalysis data are in fact more smoothed as compared to the similar variations derived from the ERA-40 data. This feature is most strongly pronounced in winter, when the high frequency of cyclones is observed over the Black Sea.

Therefore, the second time series $_{\mathrm{E40}}$ is formed of monthly mean values of the heat flux from the ERA-40 reanalysis data averaged over the whole Black Sea area. It reflects better the temporal reliability of the heat flux over the Black Sea. It should be noted that the local features of heat exchange in the area of the Caucasian coast and the southern coast of Crimea cannot be assessed from the ERA-40 data due to their low spatial resolution (1.125 along the latitude and longitude) as clear from Fig. 2b. The described circumstances make it reasonable to use two different datasets for assessing the sea-averaged and local values of heat fluxes.

To estimate the contribution of the warm branch of the Black Sea Rim Current to air temperature variations, the regression dependence of air temperature T_{ar} on two time series of heat fluxes was computed:

$$T_{\mathrm{ar}} \quad _{1} \; _{\mathrm{REA}} \quad _{2} \quad _{3}. \tag{2}$$

The interrelation between heat fluxes and air temperature is characterized by the correlation coefficient $R(T_{\mathrm{a}}, T_{\mathrm{ar}})$ and coefficients $_1$ and $_2$. The squared correlation coefficient characterizes the fraction of the variance of air temperature variability explained by regression (2); coefficients $_1$ and $_2$ describe the impact of each factor ($_{\mathrm{REA}}$ and $_{\mathrm{E40}}$) on air temperature.

The correlation coefficient $R(T_{\mathrm{a}}, T_{\mathrm{ar}}) = 0.79$ was obtained as a result of the estimation of regression dependence (2) for the southern coast of Crimea. Thus, the proposed regression explains about 62% of variance of air temperature variability in Yalta. The respective time series of parameters T_{a} and T_{ar} are presented in Fig. 3a. It should be noted that the coefficients of correlation between separate time series of heat fluxes $_{\mathrm{REA}}$ and $_{\mathrm{E40}}$ and air temperature T_{a} are equal to $R(_{\mathrm{REA}}, T_{\mathrm{a}}) = 0.52$ and $R(_{\mathrm{E40}}, T_{\mathrm{a}}) = 0.64$, respectively; this is much smaller than if both time series are simultaneously used in regression (2). The temporal variations in T_{a} in Yalta and in fluxes $_{\mathrm{E40}}$ and $_{\mathrm{REA}}$ are compared in Figs. 3c and 3e. In 1974–1976 the variations in $_{\mathrm{E40}}$ better than variations in $_{\mathrm{REA}}$ agree with variations in T_{a}. Nevertheless, the graph presented in Fig. 3c demonstrates that the heat flux variations for the time series $_{\mathrm{E40}}$ indicate incorrectly the relationship between the heat flux and air temperature in 1978–1981 and 1985–1986.

The correlation coefficient for the Caucasian coast is $R(T_{\mathrm{a}}, T_{\mathrm{ar}}) = 0.67$, and the respective time series of T_{a} and T_{ar} are presented in Fig. 3b. It should be noted that the values of correlation coefficients $R(_{\mathrm{REA}}, T_{\mathrm{a}}) = 0.56$ and $R(_{\mathrm{E40}}, T_{\mathrm{a}}) = 0.49$ are much smaller than the correlation coefficient for regression (2). The same features as on the Crimean coast are registered in temporal variations in T_{a} in Sochi and variations in fluxes $_{\mathrm{E40}}$ and $_{\mathrm{REA}}$ in the area of the Caucasian coast.

Thus, the relatively high values of correlation coefficients allow consideration that the warm branch of the Black Sea Rim Current favors the softening of climate on the eastern and northeastern coasts of the Black Sea including the southern coast of Crimea.

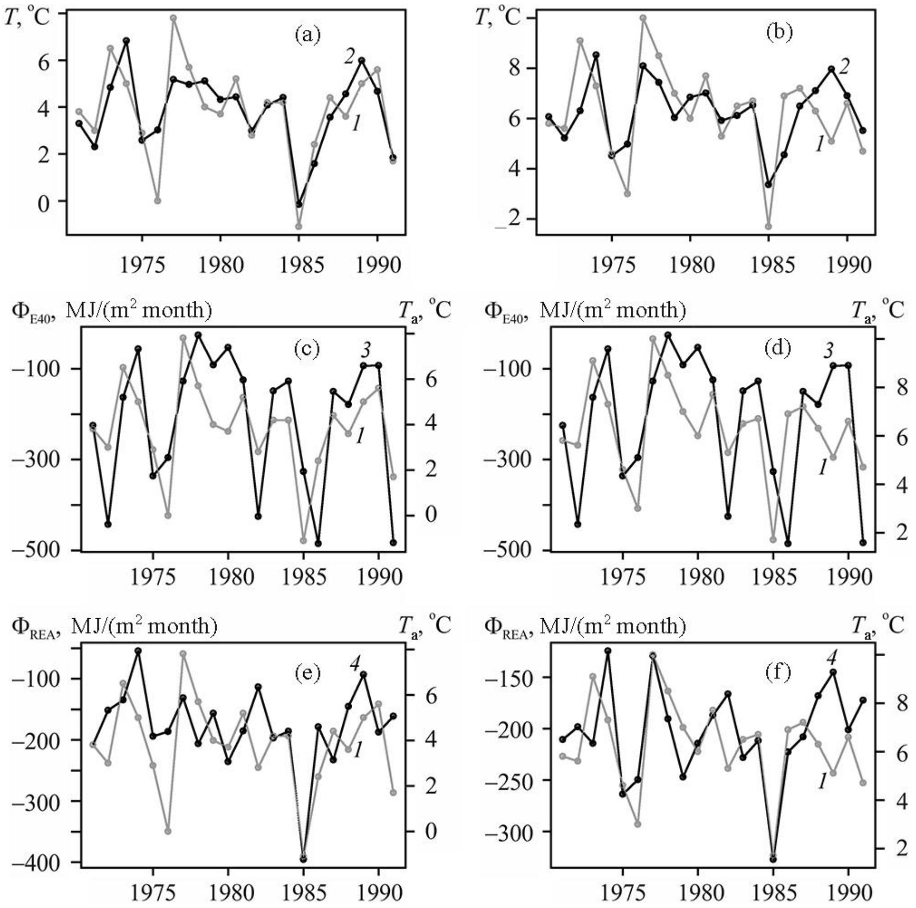

Fig. 3. The time series of (*1*) T_a, (*2*) T_{ar}, (*3*) $_{\text{E40}}$ and (*4*) $_{\text{REA}}$ in the area of (a, c, e) the southern coast of Crimea and (b, d, f) the Caucasian coast in February 1971–1991.

4. CONCLUSIONS

The results of the investigations demonstrate that the abnormally warm current spreading to the lower boundary of the active layer along the vertical was observed near the Caucasian coast and the southern coast of Crimea in winter in 1971–1991. The high values of the heat flux from the sea to the atmosphere are caused by this warm current. The shape and position of the areas of abnormal heat exchange near the Caucasian coast and the southern coast of Crimea agreed well with the shape and position of the warm water tongue in this area.

The results of the comparison of monthly mean values of heat fluxes from the sea to the atmosphere with monthly mean values of air temperature from the data of two weather stations for two areas of the Black Sea near Sochi and Yalta indicate the correlation between these parameters.

However, along with local heat fluxes, monthly mean values of temperature in the area of Yalta and Sochi are also affected by global atmospheric processes. The results demonstrate that a part of air temperature variability in Yalta and Sochi may be caused by the variability of the sea-averaged heat flux from the atmosphere to the sea driven by global atmospheric processes. The total variability of heat fluxes related to the warm current and sea-averaged heat fluxes explains 62% of variance of air temperature variability during the marine winter season in Yalta and 45% of variance of air temperature variability at Sochi weather station.

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