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# Temperature and Humidity Regime Changes on the Black Sea Coast in 1982–2014

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**Abstract**—Specific features of climate change in the Black Sea and on its northeastern coast for the period of 1982–2014 are investigated based on weather station data, ERA-Interim reanalysis, and satellite data on sea surface temperature. The main trends in air temperature and precipitation are revealed from weather station data and are compared with reanalysis data. The spatial peculiarities of variations in air temperature, integrated water vapor, moisture flux divergence, CAPE, and vertical velocity are analyzed. It is shown that air temperature variations on the coast highly correlate with sea surface temperature. In general, surface air temperature in the region has risen, especially in summer. Despite the increase in integrated water vapor and CAPE, no statistically significant increase was revealed for the mean amount of precipitation, for its intensity and maximum values. This fact might be associated with the moisture flux divergence increase in the region due to the intensification of large-scale downdrafts.

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*Keywords:* Climate of the Black Sea coast, precipitation regime, ERA-Interim reanalysis, atmospheric dynamics

## 1. INTRODUCTION

According to the data of instrumental observations, in 1983 to 2012 the global surface air temperature in the Northern Hemisphere was the highest over the recent 150 years [26]. The global warming is characterized by regional features. In particular, the authors of [3] demonstrate that the significant warming since the middle of the 1970s has been typical of Northern Europe in winter and the Mediterranean region in summer. In [13], the high spatial variability of trends in precipitation extremes for 1964–2008 is revealed for the western Black Sea coast, and these trends are statistically insignificant.

The Black Sea coast of the Caucasus is characterized by the high spatiotemporal variability of meteorological parameters. The combination of peculiarities of the large-scale circulation with local orographic conditions in the region leads to the mesoscale processes which favor the formation of numerous severe weather events. Many papers deal with the physical mechanisms and prediction potential of such severe weather events as the Novorossiysk bora [10], extreme showers and related floods [11], storm waves [9]. The results of the numerical simulation of climate for the recent decades were analyzed, and the analysis demonstrated that the considerable temperature rise in summer and the precipitation decrease might occur in the region [4]. On the other hand, it is shown for the Crimean flash flood in 2012 [20] that the sea surface temperature (SST) rise may be one of the reasons for the increase in the rate and frequency of extreme precipitation. According to model calculations, the increase in the extremity of frontal precipitation due to the convective component is expected in the south of Russia in summer in the 21st century [7].

In general, the warming is expected to lead to the exponential increase in precipitation intensity due to the increase in the moisture capacity of the atmosphere accompanied by the temperature rise (according to the Clausius–Clapeyron relation) [21, 24]. The increase in precipitation intensity might even be quicker

than the increase in the moisture content of the atmosphere, this is related to the intensification of convective processes [18].

The objective of the present paper is to analyze climate changes on the Black Sea coast in recent decades which could lead to the increase in weather-related risks in this densely populated and economically significant region. The connection of these trends with the Black Sea climate changes is important. The joint analysis is provided for the long-term trends in the regime of air temperature, SST, and precipitation derived from in situ and gridded data. The statistical generalization of observed changes is performed, and their relation to some characteristics of atmospheric dynamics is analyzed.

## 2. DATA AND METHODS

The analysis of changes in the temperature and moisture regime was based on several sources. The data of daily observations at four network weather stations were taken from the dataset of All-Russian Research Institute of Hydrometeorological Information–World Data Center (ARIHMI–WDC) [2].

| Station name | Anapa | Tuapse | Sochi | Krasnaya Polyana |
|---|---|---|---|---|
| Longitude, degree N | 44.9 | 44.1 | 43.58 | 43.6 |
| Latitude, degree E | 37.3 | 39.07 | 39.77 | 40.2 |
| Altitude, m | 30 | 60 | 57 | 566 |

Since the present research is aimed at assessing the possibility of influence of climate changes on the coastal areas in the Black Sea region, it was necessary to use additional gridded data sources. The ERA-Interim reanalysis dataset [14], NOAA OI SST V2 satellite data [23], and CRU TS 3.23 dataset [17] were also used.

| Data | ERA-Interim reanalysis | NOAA SST data | CRU TS 3.23 dataset |
|---|---|---|---|
| Horizontal resolution, degree | 0.75 0.75 | 0.25 0.25 | 0.5 0.5 |
| Temporal resolution | Month | Day | Month |
| Period (available as of March 2017) | January 1979–December 2016 | September 1981–March 2017 | January 1901–December 2014 |

The period of 1982–2014 was chosen for the analysis, because the NOAA data started from September 1981. The linear trend coefficient determined by the least-squares method as well as the value of the trend contribution to variance is used as a measure of climate changes over the selected time period. The significance of linear trends was tested using the corresponding statistical criteria with the significance level of 0.05 [5]. The specific features of the Black Sea surface temperature were assessed for several regions (see Fig. 1b). The first region characterizes the open sea and is located in its central part, the second region characterizes the northeastern part of the sea and the adjoining coastal area, and the third region includes the warm and humid eastern part of the sea and the adjoining moist subtropical coast of Abkhazia and Georgia. Except the estimates based on station data, the trends were also compared for gridded datasets.

## 3. RESULTS

### *3.1. Comparison of Station Data and ERA-Interim Reanalysis*

To determine the degree of agreement for the information used, weather station data were compared with the results of the bilinear interpolation of the ERA-Interim reanalysis data from grid points to station points over the whole analyzed period. The assessment was provided for 2-m ($T_2$) air temperature and total monthly precipitation ($P$). It should be noted that such estimates are rather frequent. For example, the authors of [25] compared data on sea surface temperature from ERA-Interim and HadSST2 reanalyses, and the average difference for 10 years (1999–2008) was equal to 0.1–0.2 C.

The analysis of correlations between station and reanalysis data for temperature (Table 1) revealed a high and statistically significant correlation: correlation coefficients were above 0.9 for all the stations. On average, the reanalysis overestimates the values of temperature at station points from 0.1 C for Anapa to 2.3 C for Sochi. However, ERA-Interim exhibited a high degree of agreement with the data of meteorological observations for temperature, so it can be used to analyze climate trends. Maximum differences in the values of trends for the whole year amounted to 0.09 C/10 years (Sochi station) (the values of trends for the stations are given in Table 2) that makes up not more than 15% of the trend value.

According to the results of comparison of station data on precipitation with ERA-Interim, the significant correlation coefficient (0.5) was obtained for Krasnaya Polyana station only. The greater differences are

**Table 1.** The results of comparison of monthly mean values for the ERA-Interim reanalysis, CRU TS 3.23 dataset, and weather stations

| Parameter | Criterion | Anapa | Tuapse | Sochi | Krasnaya Polyana |
|---|---|---|---|---|---|
| | | ERA-Interim | | | |
| $T_2$ | *R* | 0.998 | 0.996 | 0.997 | 0.996 |
| | RMS( ), C | 0.54 | 0.99 | 0.91 | 0.69 |
| | , C | 0.18 | 1.88 | 2.4 | 0.86 |
| | , C/10 years (reanalysis) | 0.75 | 0.75 | 0.67 | 0.62 |
| | *D*, % (reanalysis) | 4 | 4 | 4 | 4 |
| *P* | *R* | 0.25 | 0.2 | 0.28 | 0.48 |
| | RMS( ), mm/day | 3.53 | 1.22 | 5.91 | 4.54 |
| | , mm/day | –3.81 | 3 | 9.11 | 7.64 |
| | , mm/day per 10 years (reanalysis) | –0.02 | 0.06 | 0.12 | 0.11 |
| | *D*, % (reanalysis) | 0 | 0 | 0 | 0 |
| | | CRU TS 3.23 | | | |
| *P* | *R* | 0.91 | 0.78 | 0.93 | 0.86 |
| | RMS( ), mm/month | 16.88 | 48.77 | 33.29 | 60.98 |
| | , mm/month | 13.08 | 11.63 | 21.54 | 69.99 |
| | , mm/month per 10 years (reanalysis) | 1.56 | 0.39 | 0.76 | –1.76 |
| | *D*, % (reanalysis) | 0 | 0 | 0 | 0 |

Note: *R* is the correlation coefficient; RMS is the root-mean-square deviation, is the difference between the interpolation result and station data, is the linear trend coefficient, *D* is the trend contribution to variance.

**Table 2.** The estimates of the linear trend in temperature and precipitation characteristics for weather stations and NOAA SST for the regions separated in gridded data for the whole year and for different seasons (1982–2014)

| Station, data | Parameter | Winter | | Spring | | Summer | | Autumn | | Year | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *D*, % | | *D*, % | | *D*, % | | *D*, % | | *D*, % |
| Anapa | Air temperature, C | 0.5 | 9 | **0.5** | 21 | **1.0** | 62 | **0.8** | 27 | **0.7** | 44 |
| Tuapse | | **0.5** | 15 | **0.5** | 26 | **1.0** | 61 | **0.8** | 34 | **0.7** | 53 |
| Sochi | | 0.3 | 7 | 0.3 | 5 | **0.7** | 41 | **0.5** | 19 | 0.3 | 21 |
| Krasnaya Polyana | | **0.6** | 20 | 0.3 | 11 | **0.8** | 51 | **0.5** | 17 | **0.6** | 44 |
| Anapa | Precipitation intensity, mm/day per season | –0.1 | 2 | 0.0 | 0 | 0.0 | 0 | 0.3 | 1 | 0.1 | 0 |
| Tuapse | | –0.4 | 3 | 0.5 | 6 | –0.3 | 0 | 0.9 | 7 | 0.2 | 2 |
| Sochi | | –0.5 | 8 | 0.2 | 1 | –1.1 | 9 | 0.7 | 6 | –0.2 | 1 |
| Krasnaya Polyana | | –0.3 | 1 | 0.0 | 0 | –0.5 | 5 | 0.7 | 3 | –0.1 | 0 |
| Anapa | Total precipitation, mm/season | 0.9 | 0 | 6.0 | 2 | 5.6 | 1 | 7.5 | 1 | 20.1 | 2 |
| Tuapse | | –40.6 | 11 | 24.6 | 8 | 3.7 | 0 | 21.7 | 2 | 9.5 | 0 |
| Sochi | | –36.5 | 9 | 10.9 | 1 | –41.4 | 7 | 30.8 | 2 | –36.3 | 1 |
| Krasnaya Polyana | | –38.2 | 5 | 19.0 | 2 | –25.6 | 6 | 8.5 | 0 | –36.3 | 1 |
| NOAA SST | Sea surface | | | | | | | | | | |
| Region 1 | temperature, C | **0.4** | 55 | 0.5 | 19 | **0.8** | 54 | 0.2 | 6 | 0.5 | 5 |
| Region 2 | | **0.5** | 73 | 0.5 | 18 | **0.7** | 57 | 0.3 | 9 | 0.6 | 5 |
| Region 3 | | **0.4** | 45 | 0.4 | 13 | **0.6** | 55 | 0.4 | 11 | 0.5 | 5 |

Note: is the linear trend coefficient ( C/10 years for temperature, mm/day per 10 years for precipitation intensity, and mm/season per 10 years for total precipitation); *D* is the trend contribution to variance (%). The trends significant at the level of 5% are bolded.

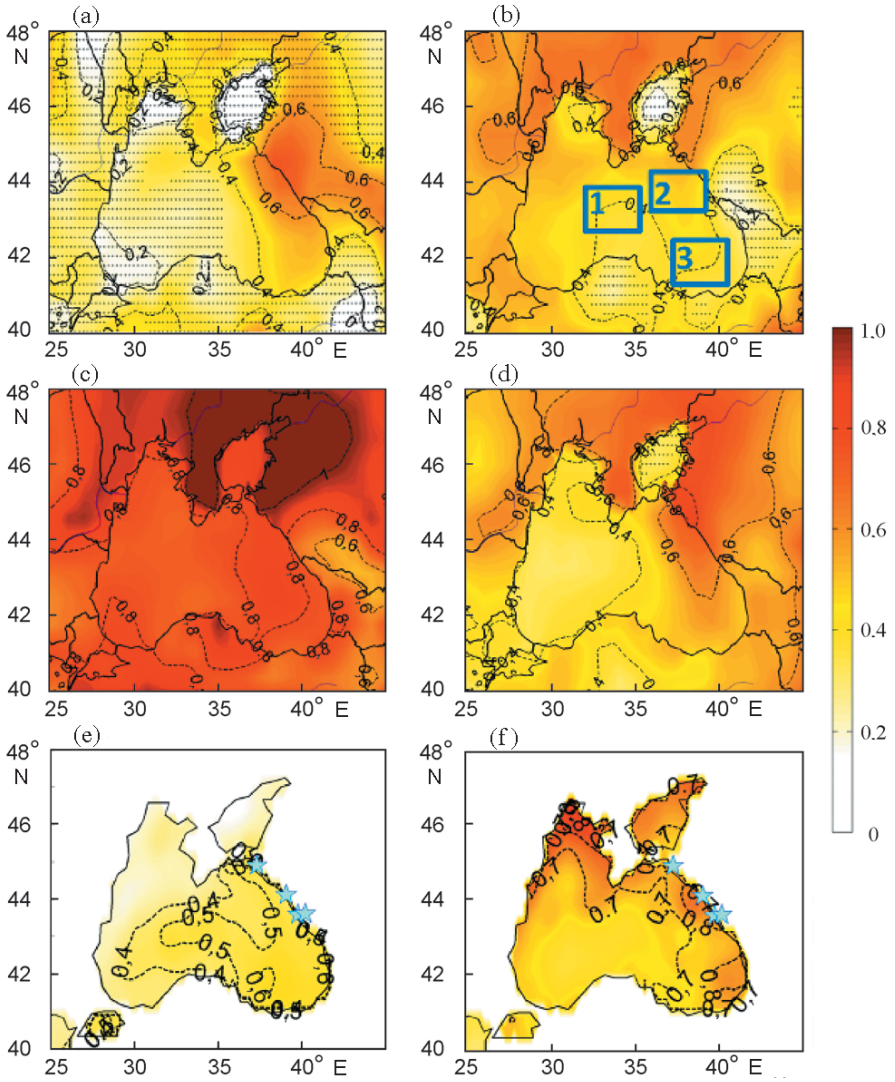


**Fig. 1.** Linear trend coefficients for 2-m air temperature ( C/10 years) from the ERA-Interim data for (a) winter, (b) spring, (c) summer, and (d) autumn in 1982–2014. The maps of regression (color) and correlation (the dotted isolines) between the SST field and air temperature (dimensionless) at the stations (marked with the blue stars) for (e) winter and (f) summer. The shaded areas are the zones with statistically insignificant trends. (b) The blue squares are the regions for which the averaging was carried out.

typical of all the other stations. The similar comparison for monthly mean precipitation from the CRU dataset revealed higher correlation coefficients, but the values of mean errors and differences in the values of linear trend coefficients indicate a poor agreement between the series. These results corroborate the low quality of precipitation simulation by most reanalyses and make the researchers use weather stations for the quantitative evaluation and consider gridded datasets as a source of additional information on probable trends for the regions which lack better data.

It is also noteworthy that the use of any gridded datasets is accompanied by the errors caused by the interpolation procedure; therefore, it is impossible to achieve the ideal agreement between reanalyses and station data. For this reason, when analyzing gridded datasets, the general spatial pattern and its variations are often considered rather than specific values at points.

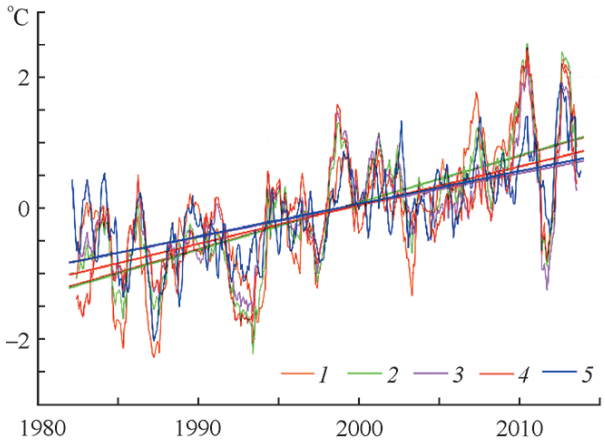


**Fig. 2.** The variations in the 11-year moving average and linear trends in the monthly mean anomalies of temperature from the data of (*1*) Anapa, (*2*) Tuapse, (*3*) Sochi, and (*4*) Krasnaya Polyana weather stations and (*5*) region 3 from the NOAA SST dataset over the period of 1982–2014 (the anomalies are computed relative to the period of 1982–2014).

### *3.2. Trends in Air Temperature and Sea Surface Temperature*

Figure 1 presents the maps of linear trend coefficients for 2-m air temperature for all seasons in the Black Sea region and the West Caucasus. The qualitative assessment of the presented data demonstrates that the warming is most strongly manifested in summer, especially in the north of the region where linear trend coefficients reach 1 C/10 years. In winter, the statistically significant warming in recent 30 years has been manifested only on the Black Sea coast and in the Caucasus mountains.

The similar trends were calculated for SST data from NOAA SST dataset and for station data on surface air temperature. The comparison was provided for the three regions described above and presented in Fig. 1b. The comparison of the anomalies of station data with SST data (Fig. 2) reveals positive trends in all selected series. Interannual and decadal temperature variations are in good agreement. The coefficients of correlation between the series of station data on temperature are from 0.75 to 0.95.

The correlations and linear regressions between the SST field and station temperature anomalies were also computed (Figs. 1e and 1f). In general, the significant correlation is registered between the values for the whole sea surface, especially in summer.

The analysis of regression maps revealed the significant correlation between the SST field and the data on temperature anomalies at station points. In winter, the zone of the maximum correlations reaching 0.7 is located in the eastern part of the sea and exceeds the correlations with SST near the stations. In summer, the correlations exceed 0.7, with the maximum values both near the Black Sea coast of the Caucasus and in the northwestern part of the sea.

The comparison of linear trend coefficients for the seasons (Table 2) suggests that the temperature rise is observed for the analyzed region based on all data sources utilized in the present paper. It should be noted that the warming trends have the highest values in winter and summer, especially for Anapa and Tuapse weather stations. In summer, the warming rate over the land is by 1.2–1.5 times higher than over the sea.

Besides the statistical analysis of surface air temperature, the changes in the thermal regime of the free atmosphere were estimated. The interest to this issue is related to the hypothesis on the general decrease in the static stability of the troposphere during the global warming [8].

The data on the rates of temperature variations at different constant-pressure levels were analyzed using the ERA-Interim reanalysis. The temperature rise in the troposphere over the Black Sea, especially in summer, is observed for all regions. For example, the significant linear trend coefficients for summer over the selected regions vary from 1 C/10 years near the surface to 0.4–0.5 C/10 years at the levels of 200–300 hPa. In winter, air temperature variations are registered only in the lower troposphere to the level of about 750 hPa, where they decrease with height from 0.8 to 0.4 C/10 years. Thus, the whole tropospheric column is warmed up in summer. In particular, this may lead to the increase in convective available potential energy.

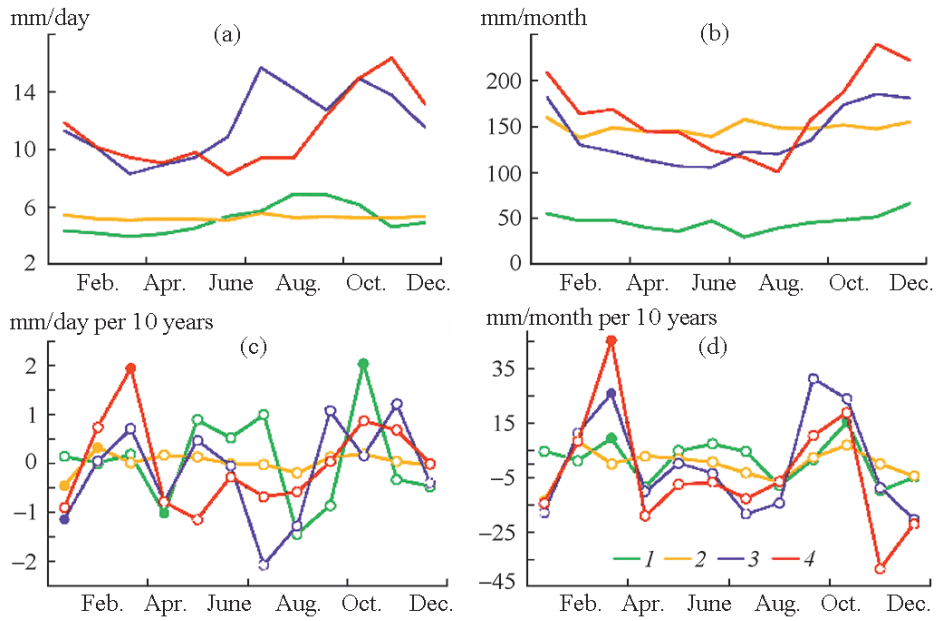


**Fig. 3.** The annual variations in (a) monthly mean precipitation intensity and (b) monthly total precipitation and the trend coefficients for (c) monthly mean precipitation intensity and (d) monthly total precipitation at (*1*) Anapa, (*2*) Tuapse, (*3*) Sochi, and (*4*) Krasnaya Polyana weather stations for the period of 1982–2014 (the significant trends are marked with the filled dots).

### *3.3. Spariotemporal Variability of Precipitation*

The peculiarities of changes in the precipitation regime for the chosen region are revealed from station data and are compared with the CRU TS 3.23 precipitation dataset.

Figure 3 presents annual variations in the monthly mean values of total daily precipitation for the days with precipitation, hereinafter called intensity (for short), as well as monthly mean total precipitation and the values of trends for these parameters. The maximum precipitation intensity in the Black Sea region falls on winter, when the Mediterranean branch of the polar front is activated here [1]. Light and moderate precipitation with the mean intensity of 2–5 mm/day is typical of the whole coast for the whole year, and the precipitation rate for the piedmont locations (Krasnaya Polyana) is higher by 5–7 mm/day on average, that is explained by the dynamic effect of terrain.

The analysis of trends in precipitation intensity and monthly total precipitation demonstrates that significant trends at the stations are observed for not more than two months per year (the significant trends are marked with the filled dots) and may be both positive and negative; therefore, it is impossible to make a general conclusion on significant variations in total precipitation and precipitation rate. Only the weak trend toward the precipitation reduction from July to September and the poorly pronounced trend towards the precipitation increase in February–March and October–November may be noted for the stations in the region.

Table 2 presents the values of linear trend coefficients for the precipitation intensity and monthly total precipitation based on station data. No statistically significant trends were detected for the precipitation intensity. In general, the certain decrease in the precipitation rate and total precipitation may be revealed for piedmont stations in summer and winter. Besides the mean values of precipitation and its intensity, the trends in the number of days with total precipitation above 15 and 30 mm and in maximum daily precipitation over the season were also analyzed. Only Tuapse station is characterized by the significant decrease in the number of days with precipitation above 50 mm (in winter). All the revealed trends for the other stations are statistically insignificant, only the weak tendencies of a sign are registered.

### *3.4. Spatiotemporal Variability of CAPE and Moisture Flux Divergence*

The interpretation of the obtained results requires analyzing the dynamics of such parameters as atmospheric integrated water vapor, moisture flux divergence, and convective available potential energy

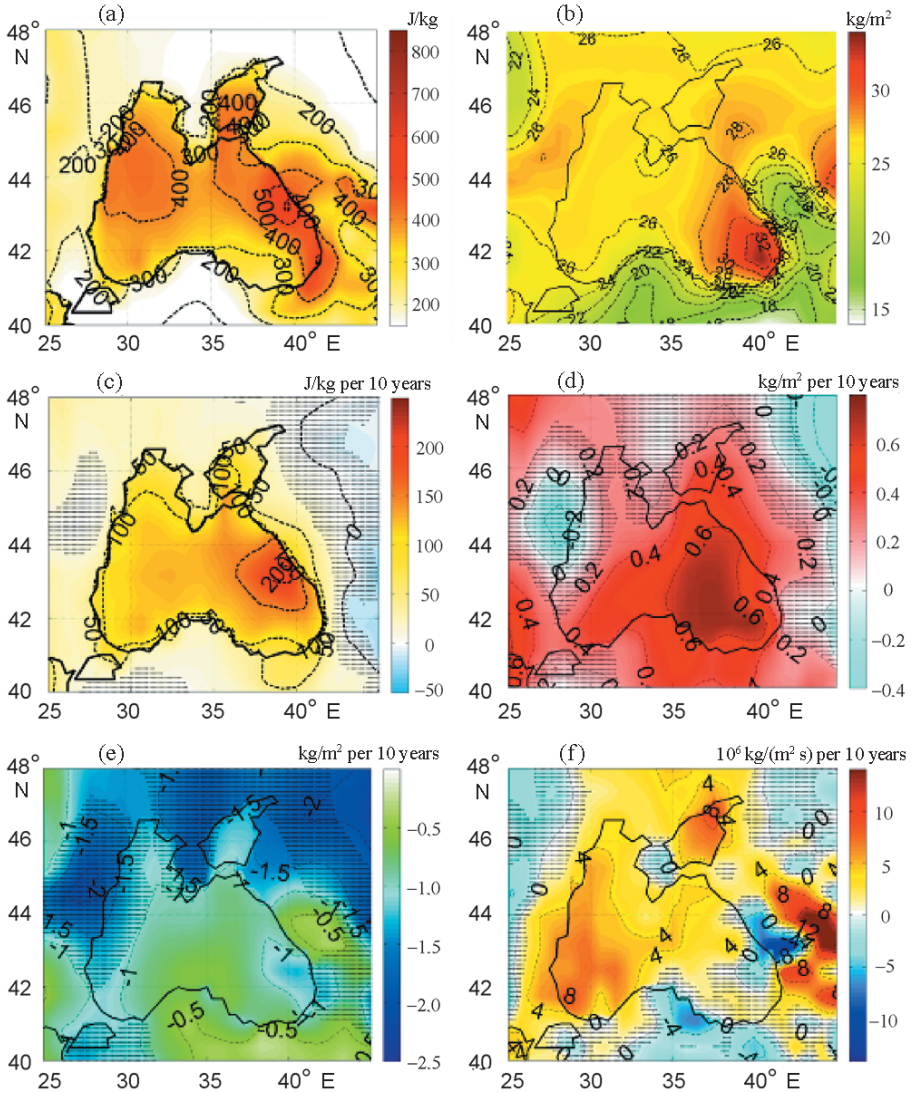


**Fig. 4.** (a, b) The summertime mean values of parameters obtained from the ERA-Interim reanalysis data: CAPE (J/kg) on the right and total column water vapor (kg/m$^2$); linear trend coefficients in summer (c) for CAPE (J/kg per 10 years) and (d) total column water vapor (kg/m$^2$ per 10 years); (e) the difference between the data obtained from ERA-Interim and the values of the trend in the total column water vapor calculated using the Clausius–Clapeyron relation (kg/m$^2$ per 10 years); (f) linear trend coefficients for the integral value of moisture flux divergence from the ERA-Interim data for summer in 1982–2014 (kg/(m$^2$ s) per 10 years). The period is 1982–2014. The zones with statistically insignificant trends are shaded.

(CAPE) which characterizes the potentially possible intensity of convective motions [22]. The ERA-Interim data were used.

The maximum values of CAPE and integrated water vapor (Figs. 4a and 4b) are observed in summer, when air contains a lot of moisture and the unstable stratification is observed near the surface. The analysis of maps of the linear trend coefficients for such parameters as CAPE and total column water vapor revealed that the most appreciable changes during the period of 1982 to 2014 can be noted for summer only (Figs. 4c and 4d). For example, the linear trend coefficient for CAPE over the central part of the Black Sea was equal to 1.8 J/kg per 10 years for winter and 126 J/kg per 10 years for summer. It was found that the values of CAPE for the given region increased by more than three times during 30 years (from 180 J/kg in 1982 to 590 J/kg in 2014). The warming rates in the upper troposphere are lower. Due to this, the mean convective instability and, hence, CAPE increase. The similar trend for integrated water vapor in the southeastern part of the Black Sea is insignificant for winter and is equal to 0.6 kg/m$^2$ per 10 years for summer. This generally agrees with the hypothesis on the essential contribution of summertime temperature variations (which

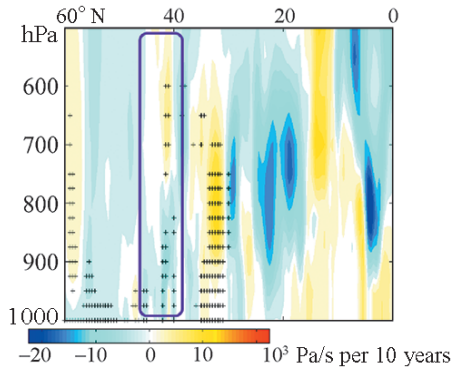


**Fig. 5.** The mean meridional section (for the zone of 35 –40 E) of linear trend coefficients (Pa/s per 10 years) for vertical velocity from the ERA-Interim reanalysis data for summer in 1982–2014 (the significant trends are shaded; the rectangle is the area under study).

define the greenhouse effect intensity due to the feedback with water vapor) to global climate changes [6]. The maximum growth of CAPE is registered in the southeastern part of the Black Sea (Fig. 4c); it is also characterized by high sea surface temperature and by the maximum values of CAPE for this sea. Thus, the CAPE growth could explain the increase in the intensity and frequency of heavy precipitation in the region; however, the analysis of weather station data indicates the opposite pattern. Consequently, other factors also affect the precipitation formation.

The data on the values of specific humidity and on temperature trends at different levels allows assessing how the temperature rise in the region under study should affect variations in total column water vapor and, perhaps, the precipitation regime. According to the Clausius–Clapeyron relation, the temperature rise in the whole troposphere by 1 C provokes the about 7% increase in its moisture content [21]. The comparison of the obtained result with actual data (Fig. 4e) demonstrates that the rate of increase in integrated water vapor in the region does not agree with the changes expected solely due to the thermodynamic effect. According to reanalysis data, the increase in integrated water vapor in 1982–2014 turned out to be by 5–15% smaller than the increase calculated from the Clausius–Clapeyron relation. This indicates the significant role of the circulation factor which evidently restrains the effect of local increase in moisture content.

The analysis of moisture flux divergence fields (Fig. 4f) revealed that summer is characterized by the positive trend in this parameter over the most of the Black Sea. The highest rates of divergence increase are typical of the central part of the Black Sea, where the divergence increases by 1.3 times per 10 years on average. The local zones of moisture flux divergence increase are registered only in the West Caucasus. Thus, the observed changes in moisture flux divergence could be a reason for the precipitation reduction in the central and northeastern parts of the Black Sea and at weather stations.

The circulation mechanism defining the moisture flux divergence increase may be associated with the variations in the intensity of large-scale meridional atmospheric circulation. For example, it is shown in [19] that the intensity of the Hadley cell decreases, but the cell expands towards the poles that influences the circulation features in mid-latitudes. The authors of [16] present the quantitative estimates of the Hadley cell expansion which on average were equal to 1 of latitude per 10 years for the Northern Hemisphere for the period of 1979–2003. The calculations of climate models also revealed that the poleward displacement of the direction of movement for mid-latitude cyclones might be observed in the 21st century [12].

After that the data on the change in vertical velocity were analyzed for the time period chosen. Figure 5 presents the results of computation of linear trends for the vertical velocity. The advection of positive vorticity (corresponding to cyclones) without account of warm advection leads to the decrease in vertical velocity that corresponds to updrafts. The advection of negative vorticity (corresponding to anticyclones) without account of warm advection leads to the increase in vertical velocity that corresponds to downdrafts [15].

In the southeastern part of the Black Sea, the increase in the intensity of vertical motions is observed in the zone of the maximum rate of CAPE growth. The rest of the analyzed territory is characterized by the decrease in the vertical component of wind speed that might be connected with the large-scale circulation change. This effect compensates the increase in total column water vapor due to the temperature rise; as a

result, total monthly and extreme precipitation in the region does not change considerably. Such mechanism may explain the results obtained for the trends in precipitation characteristics.

Thus, the reason for the stability of precipitation regime against a background of the warming in the region is a change in the type of atmospheric circulation which leads to the prevalence of downdrafts, to the moist air divergence, and, hence, to the precipitation decrease.

## 4. CONCLUSIONS

The significant temperature rise, especially over the land in summer, has been observed in the analyzed region in recent 30 years. The mean rate of warming in summer amounted to 0.84 C/10 years for weather stations, 0.7 C/10 years (from the ERA-Interim data) and 0.6 C/10 years (from the data on sea surface temperature) (NOAA OI SST V2) for the Black Sea area.

The analysis of the temporal variability of precipitation intensity in the region did not reveal such unambiguous dependences as for the temperature regime. Summer and winter months are characterized by the weak trend towards the precipitation intensity decrease; on the contrary, transition seasons are characterized by the slight trend towards the precipitation rate increase. The general trends in precipitation extremes were not detected either.

The ERA-Interim data were used for the spatial analysis of changes in temperature and moisture regimes in the analyzed region. The threefold increase in CAPE over the Black Sea in summer occurred in recent 30 years. Summer is also characterized by the warming in the whole troposphere with the mean rate from 1 C/10 years near the surface to 0.4–0.5 C/10 years at the levels of 200–300 hPa. Such significant changes should lead to the considerable intensification of convection and to the essential increase in atmospheric moisture content and, hence, precipitation. However, the trend in the total column water vapor based on the reanalysis data is much smaller than the trend expected from the Clausius–Clapeyron relation; this indicates the existence of factors restraining the precipitation increase in the region. It is demonstrated that the slowdown of moisture content increase may be caused by the increase in moisture flux divergence in the region as well as by the reduction of updraft intensity in the atmosphere. Such processes result in the fact that no noticeable change in the precipitation regime occurs against a background of the intensive temperature rise.

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