Climate variability of extreme air temperature events in the Eastern Black Sea

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Abstract
Based on the results of re-analyses, climatic changes in air temperature in the eastern part of the Black Sea over the period 1950-2015 were studied. For the regions of the coasts of the Krasnodar Territory and Abkhazia, the results of re-analyses are compared. Based on this comparison, the NCEP/NCAR re-analysis was selected, the results of which are closest to the other data sources studied for the selected region. According to the NCEP/NCAR re-analysis, climatic changes in the amplitude, frequency and duration of extreme temperature phenomena in the regions of the coasts of the Krasnodar Territory and Abkhazia over the period 1950-2015 were investigated. The analysis showed an increase in temperature since the mid-1970s, which accelerated in the late 1990s. Acceleration of temperature growth is accompanied by an increase in its interannual variability. The increase in air temperature and interannual variability is accompanied by an increase in the amplitude, number and duration of extreme events with anomalies of the positive sign. Interannual variability of extreme air temperature events characteristics is quite different for the neighbouring Krasnodar Territory and Abkhazia.

Key words: the Black Sea, regional climate change, air temperature, extreme temperature phenomena, Krasnodar Territory, Republic of Abkhazia.

Introduction
Global warming of climate leads to changes in frequency, intensity, spatial scales, duration and timing of extreme meteorological phenomena. The total number of dangerous hydrometeorological phenomena in Russia in the late twentieth and early twenty-first centuries increased on average. Of these, 52% were observed in the European territory of Russia. The North Caucasian and Southern Federal Districts of Russia and, in particular, the Black Sea coast of the Krasnodar Territory, and the Republic of Abkhazia are most susceptible to the occurrence of various extreme weather events. So in the Southern Federal District in 2010 there were 60 dangerous hydrometeorological phenomena, and in 2011 - 78. The state of the coastal ecosystems of the Black Sea region is causing serious concern, generated not only by anthropogenic but also
by natural causes (extreme meteorological phenomena, dangerous natural disasters, etc.), as well as by the frequency of their recurrence.

Under extreme meteorological phenomena are usually understood statistics of "extreme", i.e. sharply stand out against the backdrop of "norm", phenomena in the climate system. As a rule, such phenomena have a special (more often - negative) effect on natural systems, which are therefore particularly sensitive to changes in their frequency and intensity (Climate Change...., 2007; IPCC...., 2014; Shkolnik et al. 2012; An assessment report...., 2008; Second assessment report...., 2014; Karl et al. 1999).

The Fourth (2007) and Fifth (2014) Climate Change Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) indicate that in the 21st century, climate change will be accompanied by an increase in the frequency, intensity and duration of extreme natural phenomena such as: extreme precipitation or drought and extremely high or low air temperatures. All this will lead to floods, droughts, fires, shallowing of rivers, lakes and reservoirs, desertification, dust storms, melting of glaciers and permafrost, algal bloom of seas and freshwater reservoirs. In turn, these phenomena will lead to chemical and biological pollution of water, land and air. The end result of these events is deterioration in the quality of life of the population, significant financial losses associated with damage to the housing stock, businesses, roads, agriculture and forestry, tourism, and in many cases they result in human losses.

These same forecasts are confirmed by the results of the studies presented in the First (2008) and Second (2014) Roshydromet assessment reports on climate change and their consequences on the territory of the Russian Federation (An assessment report...., 2008; Second assessment report...., 2014). Forecasts of scientists have been repeatedly confirmed over the past 15 years - floods, droughts and fires in various regions of the Russian Federation, including the Krasnodar Territory, as well as in the Republic of Abkhazia, where in 2016 the amount of annual accumulated precipitation doubled the norm. In this regard, the analysis and forecasting of extreme climatic events associated with regional climate change in the territory and waters of the Krasnodar Territory and Abkhazia is an extremely important task, given the importance of agriculture and tourism for these regions.

The current state of the research on this issue is summarized in the IPCC Fifth Assessment Report on Climate Change (IPCC...., 2014) and in the Second Assessment Report of Roshydromet on Climate Change and its Consequences in the Territory of the Russian Federation (Second Assessment report...., 2014), which were published in 2014. In addition to the main IPCC assessment reports IPCC produces specialized reports on extreme events or problems (lack of water resources, etc.). Similar Annual reports on the state of the climate on the territory of the Russian Federation are issued by Roshydromet.

The disadvantage of the studies is the averaging of the parameters under study and generalization of the conclusions obtained for very large territories and water areas comparable to the size of individual countries or seas. In this work, the variability of the characteristics of extreme temperature events with a spatial scale of the order of one degree in the eastern part of the Black Sea and the coast of the Krasnodar Territory and the Republic of Abkhazia is detailed.

For the offshore area of Abkhazia, there is a lack of in-situ measurements for the statistical description of the main parameters of the state of sea water and the identification of extreme hydrological and/or meteorological phenomena. This is also true for mountain or foothill areas, where instrumental measurements of meteorological parameters are clearly not enough. For example, in (Elizbarashvili et al., 2015), based on observations from 50 meteorological stations in Georgia for 1936-2011, some temperature indexes for assessing climate change - extreme temperature values, the number of frosty, cold and hot days, tropical nights and indices based on percentiles of distribution are investigated. Geoinformation maps of the spatial structure were constructed and the dynamics of these indices during the period of global warming was investigated. Average values of indices for different averaging periods are determined. However, such a bold extrapolation of data to mountain areas leads to significant errors in estimates of climatic variability of extreme meteorological phenomena (Gruza and Ran’kova 2004). Therefore, to study the climatic variability of extreme meteorological phenomena, together with the data of meteorological observations, it is necessary to use the results of re-analyses.

Material and Methods

In this paper, the air temperature at the surface derived from the following re-analyses was studied: NOAA CIRES 20th Century Global Reanalysis Version 2c on a 2° x 2° grid for the period 1950-2011 (Campo et al.,
2011), ECMWF ERA-20C on the grid of 1° x1° for the period 1950-2010 (Stickler et al., 2014), JMA JRA-55 on the grid of 1.25° x1.25° for the period 1958-2013 (Kobayashi et al., 2015) and NCEP/NCAR Reanalysis on a grid of 2.5° x2.5° for the period 1950-2014 (Kalnay et al., 1996).

Mean values were calculated for 3 regions: the eastern part of the Black Sea (42°-45°N, 37°-42°E), Abkhazia (42°-43.5°N, 40°-42°E) and the coast of the Krasnodar Territory (43.5°-45°N, 37°-40°E). The first region of the eastern part of the Black Sea includes the regions of Abkhazia and the coast of the Krasnodar Territory, which were studied for a more detailed analysis of the features of regional climate changes and the characteristics of extreme temperature phenomena.

All results were calculated separately for each of the 3 selected regions and for each of the re-analyses analyzed. After that, the results were compared with each other in order to select the re-analysis that most closely reproduces the rest of the data sources. The differences in the air temperature variations of the coasts of the Krasnodar Territory and Abkhazia were studied.

Based on the monthly average air temperature data, the least-squares method was used to calculate the linear trends in the average air temperature in selected regions over the period under study. Then the seasonal signal was removed from the initial data at each grid node by subtracting the average intra-annual variation for the period under consideration. After that, the averaging of the anomalies of investigated parameters for the selected regions was done. Linear trends were calculated based on average temperature anomalies in the regions studied. The annual and eight-year averaging of the data series was performed. The accumulated sums of the anomalies were calculated after removing the linear trend. Mean values of the anomalies were calculated separately for each warm (May-October) and cold (November-April) half-year for the entire study period.

The results of calculation of linear trends in the series of anomalies for a single re-analyses the period 1980-2010 were summarized in Table 1. All re-analyses show a strong increase in air temperature in all the regions considered for the period 1980-2010. The temperature in the general coastal region of the eastern part of the Black Sea has least increased according to the data of 20thC_ReanV2c (by 1.2°C), and most strongly according to ERA-20C (by 2.1°C). The temperature in the region of the coast of the Krasnodar Territory increased more (by 1.4°C according to the data of 20thC_ReanV2c and 2.3°C according to the ERA-20C data) than in the region of Abkhazia (1.0°C according to the data of 20thC_ReanV2c and 2.0°C according to ERA-20C data). Linear trends for 31 year time period can be attributed to interdecadal fluctuations, and the results showed that NCEP/NCAR and JRA-55 reproduce better the other sources of data.

Table 1. Mean values of changes in temperature anomalies (°C/10 years) in the studied regions calculated by linear trends of various re-analyses for 1980-2010.

<table>
<thead>
<tr>
<th>Region</th>
<th>20thC_ReanV2c</th>
<th>ERA-20C</th>
<th>JRA-55</th>
<th>NCEP/NCAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern part of the Black Sea</td>
<td>0.387</td>
<td>0.693</td>
<td>0.435</td>
<td>0.585</td>
</tr>
<tr>
<td>Krasnodar Territory</td>
<td>0.469</td>
<td>0.756</td>
<td>0.478</td>
<td>0.681</td>
</tr>
<tr>
<td>Abkhazia</td>
<td>0.320</td>
<td>0.639</td>
<td>0.382</td>
<td>0.429</td>
</tr>
</tbody>
</table>

For comparison of air temperature variability, cross-correlations of changes in anomalies in selected regions between different re-analyses have been calculated. For comparison of intra-seasonal oscillations, cross-correlation of anomalies without filtering was investigated (Table 2). And to compare the interannual fluctuations, cross-correlation of anomalies with annual smoothing filtration are calculated (Table 3).

Table 2. Cross-correlation of changes in temperature anomalies without filtering between different re-analyses for the eastern part of the Black Sea in 1980-2010.

<table>
<thead>
<tr>
<th>Region</th>
<th>20thC_ReanV2c</th>
<th>ERA-20C</th>
<th>JRA-55</th>
<th>NCEP/NCAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>20thC_ReanV2c</td>
<td>1</td>
<td>0,89</td>
<td>0,88</td>
<td>0,89</td>
</tr>
<tr>
<td>ERA-20C</td>
<td>0,89</td>
<td>1</td>
<td>0,95</td>
<td>0,95</td>
</tr>
<tr>
<td>JRA-55</td>
<td>0,88</td>
<td>0,95</td>
<td>1</td>
<td>0,95</td>
</tr>
<tr>
<td>NCEP/NCAR</td>
<td>0,89</td>
<td>0,95</td>
<td>0,95</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 3. Cross-correlation of changes in temperature anomalies with annual filtration between different re-analyzes for the eastern part of the Black Sea in 1980-2010.

<table>
<thead>
<tr>
<th></th>
<th>20thC_ReanV2c</th>
<th>ERA-20C</th>
<th>JRA-55</th>
<th>NCEP/NCAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>20thC_ReanV2c</td>
<td>1</td>
<td>0.80</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>ERA-20C</td>
<td>0.80</td>
<td>1</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>JRA-55</td>
<td>0.84</td>
<td>0.94</td>
<td>1</td>
<td>0.93</td>
</tr>
<tr>
<td>NCEP/NCAR</td>
<td>0.84</td>
<td>0.95</td>
<td>0.93</td>
<td>1</td>
</tr>
</tbody>
</table>

In general, cross-correlations of changes in temperature anomalies for the eastern part of the Black Sea between different re-analyzes turned out to be quite high (more than 0.8). Cross-correlation of intra-seasonal changes was higher than inter-seasonal changes, which indicates a greater correspondence between re-analyzes to each other in the reproduction of short-period variability than long-period variability. Cross-correlation for the region of the Krasnodar Territory was higher than for the region of Abkhazia (no tables are given), which can be explained by the stronger influence of the mountain relief prevailing in the Abkhazian region. Analysis of intra-seasonal and interannual fluctuations showed that at these time scales NCEP/NCAR and ERA-20C reproduce better the other sources of data. Thus, for the analysis of climatic changes in extreme temperature events, the NCEP/NCAR re-analysis was chosen.

According to daily NCEP/NCAR data, for each year, the number of extreme temperature events which by modulo exceeded one and two standard deviations of the air temperature data for 1950-2015 was calculated, as well as changes in the mean amplitude and duration of these extreme events. The method of least squares for positive and negative extreme events is used to calculate the linear trends of changes in their number, average amplitude and duration.

Results

Changes of the average monthly air temperature at the surface in the region of the eastern part of the Black Sea for the period 1950-2015, when approximated by a linear trend, show an average increase of about 0.24°C in 10 years (Figure 1). This can be caused by global warming on Earth. Thus, if the changes occurring during the study period are linear, then the average temperature in the region for the considered 66 years has grown by approximately 1.6°C: from 11.4 to 13°C. That is about 8% of the yearly observed seasonal fluctuations, which are approximately 20°C: from 1-3°C to 21-23°C.

Changes in the mean monthly anomalies of air temperature near the surface in the eastern part of the Black Sea display significant interdecadal oscillations (Fig. 2). For example, in the period 1950-1958 positive anomalies were observed with respect to the linear trend, with a general decrease in temperature in the region, which led to a change of the positive anomalies to the period of the negative ones in 1959-1997. The change in the trend from a decrease to an increase in temperature in this region occurred in the mid-1970s. And since 1998, the observed growth has exceeded the linear trend, that is, there has been observed an acceleration of air temperature growth in the region. The changes that occurred in the mid-1970s and in 1998 can be explained by the transitions between the phases of the Pacific Decadal Oscillation (PDO) and the Inter-Pacific Pacific Oscillation (IPO), which led to global climate shifts (Hare and Mantua 2000; Folland et al. 2002; Mantua and Hare 2002; Chavez et al. 2003; Bond et al. 2003; Ding et al. 2013). This apparently resulted in a change in the phase of the North Atlantic Oscillation (NAO), which resulted in a change in the number of cyclones and near-surface temperature in the North Atlantic, as well as heat transfer from this region to the Euro-Asian continent, including the Black Sea region (Jung et al. 2003).

In the region there were very intensive interannual fluctuations, which demonstrated the amplification of the amplitude in the period 1950-1967, then their amplitude decreased (1968-1991), and again increased from 1992 to the early 2000s. This may be due to the fact that in the early 1970s the negative phase of the North Atlantic Oscillation shifted to positive, which caused a change in climatic scenarios in the ocean-atmosphere system of the North Atlantic (Byshev et al. 2011). The increase in the amplitude of interannual fluctuations and the increase in temperature anomalies that occurred in the first half of the 1990s may be related to the eruption of the Pinatubo volcano in 1991. After this event, approximately from 1992/93, there began to be a reduction in the heat fluxes from the ocean to the atmosphere and an increase in
the heat content of the North Atlantic (Liu et al., 2016; Serykh, 2016), which caused a change in atmospheric circulation in the region and a change in the direction of cyclones propagation (Voskresenskaya and Maslova, 2011). In recent years (2010-2015), we observe the most powerful for the whole period considered increase in interannual air temperature fluctuations in the eastern part of the Black Sea.

![Figure 1](image1.png)

**Figure 1.** Changes in mean monthly air temperature at the surface (red) and their linear trend (blue) in the eastern part of the Black Sea (42° - 45°N, 37° - 42°E).

In the region of the eastern coast of the Black Sea for the period 1950-2015 there was an increase in the amplitude of air temperature extremes with positive anomalies (Figures 3 and 4): from 3.6°C to 3.9°C for phenomena exceeding one standard deviation, and from 5.5°C to 6°C for phenomena exceeding two standard deviations. At the same time, the amplitude of extreme events with negative anomalies remained practically unchanged: 3.9°C and 7.2°C, respectively.

The number of extreme events with positive anomalies exceeding one standard deviation increased during the period under review from 10-14 to 28-32 events per year, and exceeding two standard deviations from 1-2 to 12-14 events per year. At the same time, the number of extreme events with negative anomalies decreased from 22-24 to 8-10 events per year exceeding one standard deviation, and from 5-6 to 2-3 events per year exceeding two standard deviations (Figures 3 and 4).

The average duration of extreme events with positive anomalies exceeding one standard deviation increased during the period from 2.5 to 3.5 days, but with negative anomalies practically unchanged - 3 days. The duration of extreme events with anomalies exceeding two standard deviations increased from 1 to 2 days for positive anomalies events, and remained the same (2 days) for negative anomalies (Figures 3 and 4).
Discussion

Analysis of climatic changes in air temperature and the characteristics of extreme temperature phenomena in the region of the eastern coast of the Black Sea showed an increase in temperature since the mid-1970s, which accelerated in the late 1990s. Acceleration of temperature growth is accompanied by an increase in interannual variability. The increase in air temperature and interannual variability is accompanied by an increase in the amplitude, number and duration of extreme events with anomalies of the positive sign. Interannual variability of extreme air temperature events characteristics is quite different for the neighbouring Krasnodar Territory and Abkhazia. Probably, this effect can be explained by different landscapes because Republic of Abkhazia is a mountain country and plains prevail in most of the Krasnodar Territory. This is also consistent with the detected fact that in 1980-2010 in the mountainous Abkhazia warming is about 1.5 times less intensive than in the Krasnodar Territory.

Acknowledgements

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Figure 3. The annual changes in the mean amplitude (upper part), the number (middle part) and the mean duration (bottom part) of extreme events with positive (red lines) and negative (blue lines) air temperature anomalies in the eastern part of the Black Sea (42° - 45°N, 37° - 42°E), exceeding one standard deviation, and their linear trends.
Figure 4. The annual changes in the mean amplitude (upper part), the number (middle part) and the mean duration (bottom part) of extreme events with positive (red lines) and negative (blue lines) air temperature anomalies in the eastern part of the Black Sea (42° - 45°N, 37° - 42°E), exceeding two standard deviations, and their linear trends.
References


