Climate Changes of the Temperature of the Surface and Level of the Black Sea by the Data of Remote Sensing at the Coast of the Krasnodar Krai and the Republic of Abkhazia

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Received 29 August 2017  │  Accepted 1 October 2017  │  Published online 30 October 2017.

Abstract
Climate changes in the Black Sea basin and its water area are reflected in changes in the main parameters of the sea state: sea level and sea surface temperature (SST). To study these changes, satellite altimetry and radiometry data were used that allow analyzing the spatial-temporal variability of the interannual rate of change of these parameters over a long time interval. To study the spatial-temporal variability of the rate of SST climatic variability used remote sensing data for two intervals in 1982–2015 and 1993–2015. The results of the study showed that over the time interval 1982–2015 that the SST near the coast of the Krasnodar Krai increase at an average rate of 0.079 ± 0.005°C/yr, and the coast of the Republic of Abkhazia at a rate of 0.072 ± 0.02°C/yr. At the same time, the growth rate of SST decreased from the Kerch Strait (0.082°C/yr) to Adler (0.076°C/yr), and along the coast of the Republic of Abkhazia decreased from Adler (0.076°C/yr) to Ochamchire (0.071°C/yr). In the shorter time interval of 1993–2015, which coincided with the time interval for the study of the rate of measurement of the Black Sea level, the rate of change in SST also decreased in the direction from the Kerch Strait to the border with Georgia. The results showed that for the time interval of 1993–2015, Sea level off the coast of the Krasnodar Krai increase at an average rate of 0.29 ± 0.03 cm/yr, and the coast of the Republic of Abkhazia – at a rate of 0.27 ± 0.02 cm/yr. The rate of increase in the level of the Black Sea increased from the Kerch Strait (0.28 cm/yr) to Adler (0.31 cm/yr), and along the coast of the Republic of Abkhazia, on the contrary – decreased from Adler (0.31 cm/yr) Up to Ochamchira (0.24 cm/yr).

Key words: Remote sensing, sea surface temperature, sea level, regional climatic Black Sea cost, Krasnodar Krai, Republic of Abkhazia.

Introduction
Located in the interior of the continent, the Black Sea is the most isolated part of the World Ocean. In the south-west it communicates with the Sea of Marmara through the Bosporus. The Kerch Strait connects the
Black and Azov Seas. The area of the Black Sea is 422,000 km$^2$, the volume is 555,000 km$^3$, the average depth is 1315 m, the largest depth is 2210 m. The catchment area of the rivers of the Black Sea basin is about 1,875,000 km$^2$ (of which approximately 216,000 km$^2$ is the area from An insignificant drain) (Simonov & Altman 1991; Ivanov & Belokopytov 2011).

Limited water exchange with open water areas makes the Black Sea extremely sensitive both to changes in the global and regional climate, and to the anthropogenic impact caused by river runoff and its overregulation. Among the main parameters of the Black Sea state, which reflect climatic changes both in its water area and its basin, are the sea surface temperature (SST) and its level.

**Water Balance**

The water balance of the Black Sea is composed of the following components: atmospheric precipitation (230 km$^3$/yr); continental runoff (336 km$^3$/yr); water supply from the Azov Sea (30 km$^3$/yr); Evaporation of water from the sea surface (-360 km$^3$/yr); removal of water across the Bosphorus Strait (-210 km$^3$/yr) (Simonov & Altman 1991; Goryachkin & Ivanov 2006; et al. 2008; Ivanov & Belokopytov 2011).

The main part of the river flow (up to 80%) enters the northwestern part of the sea, where the largest rivers carry water: the Danube (201 km$^3$/yr), the Dnieper (52 km$^3$/yr), the Dniester (10 km$^3$/yr), the Southern Bug (2 km$^3$/yr) and Ingle (0.2 km$^3$/yr). In total, the rivers of the north-western part discharge 270 km$^3$/yr of water per year into the sea. The rivers of the Crimean coast give about 4 km$^3$/yr, the river of the Turkish coast is estimated at 26 km$^3$/yr, and the rivers of the Bulgarian-Romanian coasts are 3 km$^3$/yr (Simonov & Altman 1991; Goryachkin & Ivanov 2006; et al. 2008). Relatively much river water receives sea along the Caucasian coasts 43 km$^3$/yr (Bulgakov & Yurkova 2000; Jaoshvili 2002).

The length of the Black Sea coast of the Krasnodar Krai (from the Kerch Strait to the mouth of the Psou River) is about 400 km, and the length of the coast of the Republic of Abkhazia (between the Psou and the Enguri River) is more than 240 km (Fig. 1). The entire region of the Black Sea coast of Russia and the Republic of Abkhazia can be divided into three large areas – Kerch-Taman, West-Caucasian and Colchis (Belyuchenko 2005; Adzinba & Bogaychuk 2011).

**Figure 1.** The Black Sea coast of the Krasnodar Krai and the Republic of Abkhazia.
The rivers of the Black Sea coast along the water regime can be divided into two groups. The first group consists of the rivers of the Mediterranean climate (dry subtropics), located north-west of the city of Tuapse, they are characterized by a flood regime in the cold part of the year and a steady low level from May to October. Summer low water is occasionally interrupted by floods, which sometimes have a catastrophic character. The second group includes the rivers of the humid subtropical climate of the Greater Sochi region and the Republic of Abkhazia. For them, floods are typical at any time of the year, a low-water period, often interrupted by floods (Belyuchenko 2005; Adzinba & Bogaychuk 2011).

Within the Black Sea coast of the Krasnodar Territory there are up to 80 small rivers that have access to the sea. Only three of them – Mzymta, Shahe and Psou – have a length of more than 50 km and a catchment area of more than 400 km². The total annual flow of fresh water to the Black Sea from the coast of the Krasnodar Krai reaches 7.5 km³/yr (Mzymta – 1.4 km³/yr, Shahe – 1.0 km³/yr, Psou – 0.65 km³/yr) (Belyuchenko 2005; Korovin 1979).

About 120 rivers of Abkhazia annually carry more than 13 km³ of water to the sea. The largest river of Abkhazia is the Bzyb’ River, which stretches from the source to the mouth of 112 km. The average annual flow of the Bzyb’ River is about 3 km³/yr. The second major river of Abkhazia is Kodori, (formed from the confluence of the rivers Sakeni and Gvandra), the length of which (together with Saken) is 105 km. The average annual flow of the Kodori River is about 4.5 km³/yr (Adzinba & Bogaychuk 2011).

Analysis of data on the monthly and annual values of the total river flow into the Black Sea over a long period of time indicates the absence of a significant impact of the anthropogenic factor (Ivanov & Belokopytov 2011). Important is, apparently, climate change, which affects the moisture content of the sea basin. So in the period 1860–2008. The annual runoff of the Danube River increased with a noticeable interannual variability on average with a positive trend of 0.126 km³/yr (Reva 1997; Goryachkin & Ivanov 2006; Mikhailov & Mikhailova 2008; The second assessment… 2014; Kostyanoy et al. 2014).

Material and Methods

Sea surface temperature (SST) is one of the first oceanographic parameters, which began to be measured from the board of satellites (Lavrova et al. 2011). It is calculated from data on the radio brightness temperature, measured by IR and microwave radiometers, and from data from visible scanners that have an additional channel in the infrared range. The accuracy of the SST calculation for various types of radiometers is presented in Table 1. To study the interannual variability of the Black Sea SST, the data of the international project SST_BS_SST_L4_REP_OBSERVATIONS_010_022 (Buongiorno 2014) were used. They represent the average daily SST fields on a regular grid with a pitch of 0.03° on latitude and 0.02° on longitude from September 1982 to December 2015.

Sea level anomalies (SLA) were calculated from the altimetric measurements of the TOPEX/Poseidon, ERS–1/2, GFO–1, Jason–1/2/3, ENVISAT and SARAL/AltiKa satellites. The accuracy of SLA calculation for different types of altimeters is presented in Table 2. To analyze the interannual variability of SLA, combined altimetric measurements were used, created within the framework of the SSALTO/DUACS project (2016). They represent the average daily TST fields on a regular grid in increments of 0.125° on latitude and longitude from September 1992 to December 2015.

Results and Discussion

According to the results (Fig. 2–3) for the entire region the SST grows at a rate of 0.078±0.005°C/yr for the period from 1983 to 2015. At the coast of the Krasnodar Krai, SST grew at an average rate of 0.079±0.005°C/yr, and on the coast of the Republic of Abkhazia - at a rate of 0.072±0.002°C/yr. At the same time, the growth rate of SST decreased from the Kerch Strait (0.082°C/yr) to Adler (0.076°C/yr), and along the coast of the Republic of Abkhazia decreased from Adler (0.076°C/yr) to Ochamchire (0.071°C/yr) (Fig. 2). The maximum rate of SST interannual variability (more than 0.083°C/yr) is observed in the open sea from the Kerch Strait to Tuapse, and the minimum – in the border area of Abkhazia and Georgia.

In the shorter time interval of 1993–2015, which coincided with the time interval for studying the rate of measurement of the level of the Black Sea, the rate of change in TMP also decreased in the direction...
from the Kerch Strait to the border with Georgia. However, the minimum values are observed not only in the border area of Abkhazia and Georgia, but also in the area of Tuapse–Gagra (Fig. 3).

**Table 1.** The main types of sensors SST measurement from the board satellite (Lavrova et al. 2011; Lebedev & Shauro 2011).

| Sensor Type | Name (full and short) | Width scopes (km) | Spatial resolution (Km) | Accuracy (°K) |
|-------------|-----------------------|-------------------|------------------------|--------------|
| Infra-red radiometer | Advanced Very High Resolution Radiometers (AVHRR) | 2600–4000 | 1.10–4 | 0.3–0.5 |
| | Along-Track Scanning Radiometer (ATSR) | 500 | 1 | 0.3 |
| | Visible Infrared Spin-Scan Radiometer (VISSR) | 120 | 5 | 0.8 |
| Spectro-radiometer | Moderate-resolution Imaging Spectroradiometer (MODIS) | 2330 | 1 | 0.3 |
| Microwave radiometer | Special Sensor Microwave Imager (SSMI) | 1400 | 25 | 0.6–0.7 |

**Table 2.** The main mission of satellite altimetry measurements and their accuracy (Lavrova et al. 2011; Lebedev & Shauro 2011).

| Satellite | Active time (month/year) | Altimeter | Spatial resolution (m) | Accuracy (cm) |
|-----------|--------------------------|-----------|-----------------------|--------------|
| TOPEX/Poseidon | 08/1992 – 01/2006 | NRA | 700 Poseidon-1 | 1.7 |
| ERS-2 | 04/1995 – 06/2002 | RA | 530 | 3.0 |
| GFO-1 | 02/1998 – 09/2008 | GFO-RA | 570 | 3.5 |
| Jason-1 | 12/2001 – 07/2013 | Poseidon-2 | 700 | 1.7 |
| ENVISAT | 03/2002 – 04/2012 | RA2 | 540 | 4.5 |
| Jason-2 | 06/2008 – 05/2017 | Poseidon-3 | 700 | 1.7 |
| HaiYang-2A | 08/2011 – present time | HY-2A | 965 | 4.0 |
| SARAL/AltiKa | 02/2013 – present time | AltiKa | 786 | 2.5 |
| Jason-3 | 01/2016 – present time | Poseidon-3 | 700 | 1.7 |
On the basis of these data, the monthly and annual fields of the SST and SLA were designed on a grid with the same spatial resolution.

Figure 2. Spatial variability of the climatic rate of SST change (°C/yr) for period from 1983 to 2015.

Figure 3. Spatial variability of the climatic rate of SST change (°C/yr) for period from 1993 to 2015.
For the time interval of 1993-2015 The Black Sea level off the coast of the Krasnodar Territory grew at an average rate of 0.29±0.03 cm/yr, and the coast of the Republic of Abkhazia – at a rate of 0.27±0.02 cm/yr. At the same time, the rate of increase in the level of the Black Sea increased from the Kerch Strait (0.28 cm/yr) to Adler (0.31 cm/yr), and along the coast of the Republic of Abkhazia, on the contrary – decreased from Adler (0.31 cm/yr) To Ochamchire (0.24 cm/yr) (Fig. 4).

**Figure 4.** Spatial variability of the climatic rate of the Black Sea level change (cm/yr) for period from 1993 to 2015.

**Acknowledgements**
The reported study was funded by RFBR according to the research project № 17-55-40015_Abh_a «Climate changes of intensity and frequency of extreme hydrological and meteorological events in the coastal zone of the Krasnodar Territory and Abkhazia».

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