General features of air temperature over coastal waters of the south-eastern Baltic Sea for 2004–2017

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The paper is devoted to the analysis of air temperature variability over the coastal waters of the south-eastern part of the Baltic Sea. The study uses the data from the automatic hydrometeorological station located 20 km from the coast on the offshore ice-resistant fixed platform. The annual mean air temperature is 8.8 ± 0.6°C, which is 1.4°C higher than in the middle of the last century. The annual minimum of air temperature (−0.3°C) has shifted towards February, therefore the climate of the south-eastern Baltic Sea has become more marine. The rise of monthly mean air temperature in 2004–2017 has revealed at a rate of +0.005°C/month, i.e. +0.8°C/period (according to the hourly observations of air temperature the increase accounts for 0.95°C for the same period). The greatest contribution to the variability of annual mean values of air temperature is provided by variations in the cold season (February and March). A close relationship between the North Atlantic Oscillation index and the air temperature is shown (correlation coefficient $r = 0.7$), which explains the dependence of detected air temperature variability from the circulation conditions. The lower values of the North Atlantic Oscillation index stipulate the intensification of anticyclonic activity and noticeable decrease of air temperature in the study area. The predominance of a positive phase of the North Atlantic Oscillation index causes the strengthening of the Icelandic Low and a west-east transfer what consequently results in the increase of air temperature. Western form of circulation by Wangenheim-Girs is prevailing in the study area. However, the enhancement of the eastern form of circulation by Wangenheim-Girs slows down the increase of air temperature. *KEYWORDS:* Variability; air temperature; fluctuations; Baltic Sea; circulation; correlation.

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Introduction

Recently, the variations of hydrometeorological conditions have become evident in the Baltic region, as well as in the other regions of Europe. In most studies these variations are associated with anthropogenic impact [*IPCC,* 2008; *Stocker et al.,* 2013]. The instrumental data indicate the increase of subsurface air temperature in temperate latitudes and cyclic variations in temperature over several decades [*Alekseev et al.,* 2010; *Kotlyakov,* 2010; *Panin,* 2010]. Following *Alekseev et al.* [2010] and *Frolov et al.* [2010], the observed warming is caused by natural factors which vary over a time scale of tens to hundreds of years, and is not affected by anthropogenic influence. Despite the regional differences, the common patterns of long-term variability of mean air temperatures are noticeable in

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the coastal areas of the Baltic Sea [*Chubarenko and Chubarenko,* 2002]. The paper [*Avotniece et al.,* 2010] showed that the duration of vegetation and frost-free period increased because of the high summer temperature and the decrease of extreme values of temperature in winter. The increased frequency of the exceptionally hot summer months and even entire summer seasons was revealed in Europe in the last decade of the XX century and in the first decade of the XXI century [*Twardosz and Kossowska-Cezak,* 2013]. The variability of the minimum and maximum temperature and the daytime temperature range in Poland were analyzed using the data from 9 stations with different data periods (the longest dataset is 98 years) [*Wibig and Głowicki,* 2002]. The increase of the minimum temperature was accompanied by a slight rise of the maximum temperature and a decrease of the daytime temperature range. It has been established that these changes correlate well with cloudiness while strong temperature fluctuations are associated with the intensity of the North Atlantic Oscillation (NAO) especially in winter and spring. In the Baltic countries average air temperature anomalies in 1991–2007 accounted for 0.8–0.9°C relative to the climatic period of 1961–1990 and the increase of precipitation was also observed (1–6%) especially in winter [*Kriauciuniene et al.,* 2012]. The linear trend of air temperature for the entire Baltic coast of Poland was equal to 0.3°C/decade for the period 1966–2009 [*Tylkowski,* 2013]. But the regional differences were notable. Thus, the maximum increase of air temperature (0.32°C/decade) occurred on the Szczecin Coast, located in the western part of the Baltic Sea Polish coast, while in the eastern part, on the Gdansk Coast, the trend was weaker (0.28°C/decade) [*Michalska,* 2011]. The seasonal linear trends of air temperature in the area of Szczecin were obtained for 1950–2009: 0.0296°C/year in spring and 0.032°C/year in winter (1.8 and 1.9°C/60 years respectively) [*Kirschenstein,* 2011].

The total solar radiation reaching the south-eastern Baltic Sea equals to 360.0–376.8 kJ/cm^2 per year [*Pomeranets,* 1964; *Samoylenko,* 1957; *Terziev et al.,* 1992]. The distribution of cloudiness and atmospheric transparency significantly affects the solar radiation supply. The south-eastern Baltic Sea receives more than 45% of the annual sum of absorbed solar radiation in summer, a little less in spring (approximately 35%), and 20% in cloudy autumn-winter season. The radiation balance is negative during 4–5 months (from October–November to February–March) in the study area. The minimum of solar radiation is observed in December and the maximum values are noted in June [*Dubravin and Stont,* 2012; *Terziev et al.,* 1992].

There is an opinion [*Pinker et al.,* 2005; *Wild et al.,* 2005], that the amount of solar radiation reaching the Earth's surface has recently increased in comparison with 1990. This is one of the reasons for the increase of air and sea surface temperatures. The total solar radiation shows the positive trend since the mid-1980s for the Moscow region [*Chubarova et al.,* 2014].

Following *Smirnova et al.* [1988], the increase of air temperature in different coastal areas of the White and the Baltic Sea has been observed since the beginning or middle of 1980s, and in spite of the global warming, the solar activity secular minimum was expected in 2016. According to the World Data Center for the production, preservation and dissemination of the international sunspot number of Royal Observatory of Belgium (World Data Center for the production, preservation and dissemination of the international sunspot number, Royal Observatory of Belgium, URL: http://sidc.be/silso/home). the deepest part of the minimum should be in 2018–2019 and the increase of solar activity is predicted from the middle of 2019.

The goal of the study is to analyze the variability of air temperature in the Russian sector of the south-eastern Baltic Sea.

Materials and Methods

The research was carried out on the basis of a 14-year series of observations in the open part of the sea, where the influence of land is excluded (Figure 1). Hydrometeorological observations in this part of the south-eastern Baltic Sea are almost absent in recent years. The study area is located outside the active shipping routes, i.e. there are no simultaneous measurements on board transport, passenger, and fishing vessels.

We used the data of the automatic hydrometeorological station mounted on the offshore ice-

Figure 1. Study area. The asterisk shows the location of offshore ice-resistant platform (D6) and automatic hydrometeorological station (AHMS), red lines – the boarders of the Russian exclusive economic zone.

resistant fixed platform OIFP (D6), located approximately 20 km from the coast (Figure 1). The automatic hydrometeorological station (AHMS) "MiniKrams-4" is installed on the offshore platform (D6) at a height of 27 m above the sea level and provides continuous measurements. The AHMS software is able to encode meteorological parameters using the international code FM 12-IX SYNOP and transmit the data via the Internet channel, which allows the operational processing of observational data. We analyzed the hourly measurements of air temperature, which represent a continuous dataset for 14 years. The air temperature was not reduced to a standard 2 m level, since it was difficult to take into account the factor of atmospheric stratification.

The annual mean air temperature was calculated by averaging the hourly measurements with a uniform pitch (1 hour). Afterwards spline interpolation was used to smooth the dataset.

The interannual variations of air temperature were investigated using variance and harmonic analyzes [*Bruks and Karuzers,* 1963; *Kozubskaya and Konyaev,* 1977; *Rozhkov,* 2008]. The long-term trends were calculated by linear approximation of the time series using the least squares method. The statistical significance of the linear dependence coefficients and the reliability of the obtained results

Table 1. Interannual Variations of Air Temperature From OIFP D6 for 2004–2017

Year	Mean, °C	Extreme values, °C		
		minimum	maximum	amplitude
2004	8.4	−10.6	25.9	36.5
2005	8.9	−9.7	24.4	34.1
2006	9.0	−19.3	29.8	49.1
2007	9.3	−12.3	26.4	38.7
2008	*9.4*	−10.3	22.9	33.2
2009	8.7	−10.9	26.7	37.6
2010	*7.2*	−15.3	31.1	46.4
2011	8.9	−13.1	28.0	41.1
2012	8.2	−16.4	29.4	45.8
2013	8.7	−10.9	30.7	41.6
2014	9.2	−12.3	26.8	39.1
2015	*9.4*	−7.2	28.5	35.7
2016	9.2	−13.2	29.6	42.8
2017	8.8	−10.1	25.2	35.2
Mean $\pm\sigma$	8.8 ± 0.6	-12.2 ± 3.1	27.5 ± 2.5	39.8 ± 4.9

Note: Extreme values are marked in italics.

were evaluated using the Student's t-test. The possibility of sampling by seasons and months was provided for investigation of the linear model parameters. The spline interpolation of data was additionally performed to obtain series with even time step and identify long-term variations. Seasonal statistics and the general trend (the whole dataset) are non-additive.

The daily NAO index was used to distinguish the NAO phases. The daily NAO indices are provided by the National Weather Service of National Oceanic and Atmospheric Administration, USA (Daily NAO index since January 1950, National Weather Service of National Oceanic and Atmospheric Administration, USA, URL: http://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.index.b500101.current.ascii) and calculated using the rotated principal component analysis [*Barnston and Livezey,* 1987].

Results

Following [*Sustavov,* 1983] the annual mean air temperature in the study area was 7.4°C at the end of the XX century, and the lowest monthly temperature (−2.0°C) was observed in January. During summer the average temperature was 16.8°C, and the highest values occurred in August (16.9°C). The annual amplitude of monthly mean temperature was 18.9°C [*Sustavov,* 1983].

The main features of air temperature interannual variability obtained from OIFP D6 for the period 2004–2017 are presented in Table 1 and Figure 2. The annual mean air temperature is higher than in the middle of the last century [*Sustavov,* 1983] and accounts for 8.8 ± 0.6°C, the annual amplitude of monthly mean values equals to 19.7°C (Table 2). The maximum annual mean temperature is observed in 2008 (9.4 ± 5.8°C) and in 2015 (9.4 ± 5.6°C). The variations of monthly mean values range from 2.4°C (January) to 18.0°C (July) and from 1.9 (January) to 19.3°C (July) respectively. The minimum annual mean temperature occurs in 2010 (7.2 ± 8.6°C), and monthly mean temperature values vary from −5.4 to 20.8°C.

The interannual distribution of the linear trend increment of annual mean air temperature in 2004–2017 ranges from −1.5 to 1.7°C (the mean value is 0.3 ± 0.8°C). The interannual trend increment of the maximum monthly mean values varies from −0.3 to 2.2°C, while the increment of minimum monthly mean values fluctuates from −2.1 to 2.3°C that is approximately 2 times greater than for the warmest months of the year. This result indicates that temperature variations during the cold period of the year provide the greatest contribution to the variability of annual mean values of air temperature. Thus in 2008 (the warmest year) only 10 days with frosts down to −10°C were observed during winter.

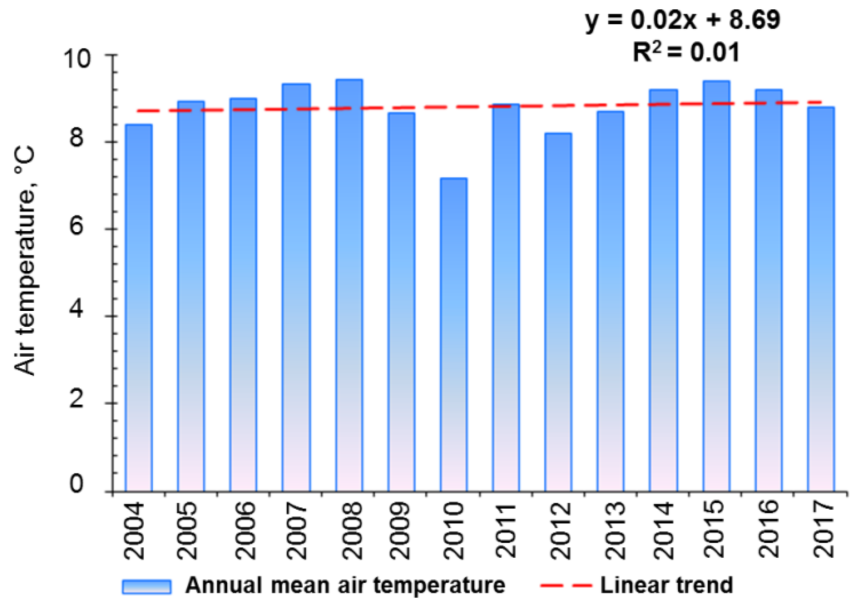

Figure 2. Interannual variations of air temperature from OIFP D6 for 2004–2017. The linear trend is shown with a red line.

In winter period in 2010 (the coldest year) the total duration of freezing days (up to −15°C) was 60 days [*Stont and Demidov,* 2015].

In winter the monthly mean air temperature of two months (January and February) declines to negative temperatures (−0.2°C and −0.3°C respectively). The minimum of annual variation moves towards February (−0.3°C) in comparison with the minimum that appeared in January (−2.0°C) in the middle of the last century (Table 2). This phenomenon is probably caused by the circulation processes.

Meanwhile, the recurrence of the winds of the east points has increased in February in the same years, when the negative temperatures were observed. The shift of the monthly mean temperature minimum from January to February reveals that the climate of the south-eastern Baltic Sea

Table 2. Statistical Characteristics of Monthly Mean Air Temperature Measured on OIFP D6 in 2004–2017 and Values of Linear Trend Increment per Month

Statistical characteristics	Months I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Mean, °C	−0.2	−0.3	2.2	6.0	10.9	14.5	18.2	18.6	15.6	10.5	6.4	3.5
Standart deviation, ±σ	2.76	2.44	2.02	1.16	1.14	1.55	1.54	0.65	0.95	1.42	1.03	2.76
Absolute maximum, °C	10.3	7.4	15.8	21.3	26.1	29.8	31.1	29.1	24.1	18.2	12.8	12.3
Absolute minimum, °C	−19.3	−16.4	−9.7	−1.1	2.8	7.7	12.1	11.7	7.0	1.1	−9.2	−11.5
Trend increment, °C	−0.6	2.3	2.2	0.1	1.8	0.5	−0.8	0.04	−0.6	−2.4	0.7	−0.1
Student's coefficient	5.844	17.602	28.815	0.970*	13.648	4.702	8.290	0.520*	7.534	23.425	6.984	0.739*
Number of observations	10083	9219	10221	9790	10189	9720	10045	10149	9765	10152	9794	10057

Note: * statistically not significant (p-level > 0.01).

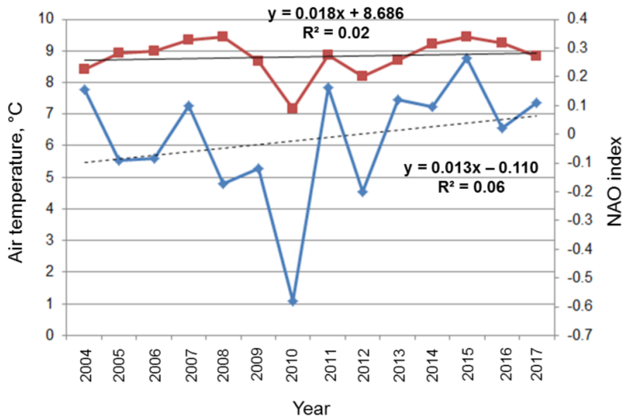

Figure 3. Interannual variations of air temperature and NAO indices. The red line shows the air temperature distribution, the blue line – the NAO index. The linear trend of air temperature is shown with a solid line, the linear trend of the NAO index – dotted line.

has become more marine. The absolute minimum $-19.3°C$ (in January) was observed in 2006, the maximum amplitude of extreme values was 49.1°C this year (Table 1). The air temperature is most changeable in winter – for December and January the standard deviation ($\pm\sigma$) is the highest and accounts for 2.76°C (Table 2). This fact is provoked by the circulation conditions: the frequent alternation of thaws during invasion of Atlantic cyclones and cold air inflows under increasing influence of anticyclones.

The seasonal increase of air temperature occurs evenly from March to August – from 2.2°C (March) to 18.6°C (August) (Figure 2, Table 2). Since 2004 the monthly mean temperature of the warmest month (August) has increased by 1.7°C relative to the second half of the XX century. The monthly mean temperature in August is the least changeable ($\pm\sigma = 0.65°C$). The temperature of July is 0.4°C lower (18.2°C), while in June the monthly mean temperature is 14.5°C. The air temperature during the spring transitional period is estimated as 2.2°C in March, 6.0°C in April, and 10.9°C in May. The autumn period shows the following values of monthly mean temperature: 15.6°C in September, 10.5°C in October, and 6.4°C in November. The periods of temperature increase and decrease in the seasonal cycle are approximately equal and amount to 6 months, i.e. the seasonal variation of air temperature in the study area is determined by the annual wave.

The variation of air temperature in the study area is characterized by a linear trend of +0.02°C/year. Thus, a warming rate accounts for 0.20°C/decade and 0.28°C/period (Figure 2). This result totally corresponds to the estimations of linear trends, obtained for the eastern coast of Poland (+0.28°C/decade for 1966–2009) by *Michalska* [2011] and for Kaliningrad (+0.20°C/decade for 1996–2010) by *Navrotskaya and Stont* [2014].

A positive trend increment of the monthly mean air temperature is observed from February to June. The maximum positive increments appear in February (2.3°C per period) and March (2.2°C per period) with high statistical significance ($p < 0.01$) (Table 2). The maximum negative increment occurs in October $-2.4°C$/period. In August the increment is close to 0°C/period (statistically not significant $p > 0.01$). Following *Jurgelėnaitė et al.* [2012] the rate of change in the air temperature in Lithuania was estimated as 0.06°C/warm season for 1991–2010, which is in a good agreement with our estimation.

Discussion

Western (W) circulation form by Wangenheim-Girs has prevailed in the Atlantic-European region over recent decades [*Dmitriev et al.,* 2018]. The increase of solar radiation reaching the Earth's surface has declared [*Pinker et al.,* 2005; *Wild et al.,* 2005]. These two factors induced the rise of monthly mean air temperature in winter (up to $-0.3°C$ against $-2°C$ in the middle of the last century) and the shift of annual minimum temperature towards February.

The intensification of anticyclonic activity in the study area occurs during the periods with lower values of the NAO index (in our study 2005–2012, excluding 2011) (Figure 3, Table 3). Thus, in 2010 the negative NAO phase prevailed, as a result winter frosts reached $-15°C$, while in summer temperature increased up to 31°C. Overall 2010 appeared as the coldest year in the period of observation (Table 1).

The positive phase of the NAO index has dominated since 2013 (Figure 3). This stipulates the strengthening of the Icelandic Low, the reinforcement of the west-east transfer, and consequently

Table 3. Annual mean values of air temperature, western (W), eastern (E), meridional (C) circulation forms by Wangenheim-Girs, and the NAO index

Year	Air temperature	W	E	C	NAO index
2004	8.4	144	136	86	0.155
2005	8.9	134	147	84	−0.091
2006	9.0	123	153	89	−0.085
2007	9.3	138	132	95	0.1
2008	9.4	179	119	68	−0.172
2009	8.7	126	155	84	−0.119
2010	7.2	108	163	94	−0.582
2011	8.9	143	153	69	0.164
2012	8.2	143	141	82	−0.202
2013	8.7	122	145	98	0.12
2014	9.2	94	177	94	0.094
2015	9.4	145	128	92	0.264
2016	9.2	103	160	103	0.02
2017	8.8				0.108

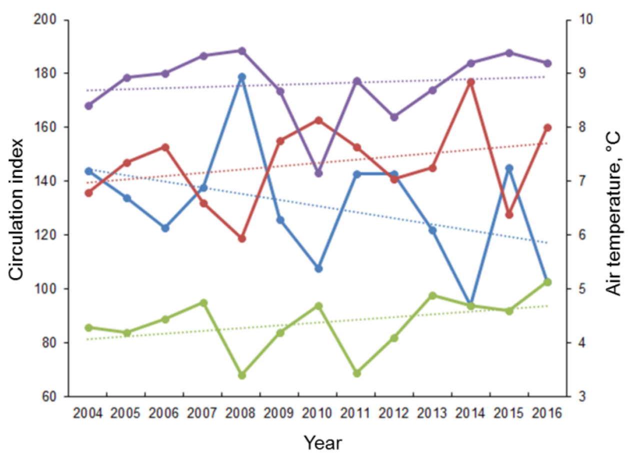

Figure 4. Interannual variations of air temparature and circulation indices by Wangenheim-Girs for 2004–2016. The purple line shows the air temparature, the red line shows the eastern circulation form, the blue line shows the western circulation form, the green line – meridional circulation form. The dotted lines show the respective linear trends. The equation of air temparature linear trend is $y = 0.02x + 8.672$ ($R^2 = 0.02$); the linear trend of the eastern circulation form is $y = 1.242x + 138.15$ ($R^2 = 0.09$); the linear trend of the western circulation form $y = -2.253x + 146.69$ ($R^2 = 0.16$); the linear trend of the meridional circulation form is $y = 1.011x + 80.462$ ($R^2 = 0.14$).

the increase of air temperature. The correlation coefficient r calculated between the NAO index and air temperature for 2004–2017 equals to 0.7 (p-level < 0.05), what proves a quite close relationship (according to the Cheddock scale).

In 2004–2016 activation of the eastern (E) circulation form was observed (Figure 4). A blocking anticyclone over Eastern Europe took place and Atlantic cyclones, enveloping Scandinavia, penetrated far into the Arctic and carried the heat [*Dmitriev et al.,* 2018]. This high-latitude zonality has led to retardation of air temperature increase in the south-eastern part of the Baltic Sea.

Comparison between interannual variability of the air temperature and the Wangenheim-Girs circulation indices reveals that the positive air temperature trend stems from the positive trends of the eastern and meridional circulation forms and the negative trend of the western circulation form (Figure 4). The maximum annual temperature (2008, 2015) corresponds to the high value of the western form index and the minimum value of the eastern circulation form index. The minimum annual air temperature (2010) appears when the maximum values of the eastern circulation index occur (with dominating of anticyclones with eastern winds in winter) [*Stont and Demidov,* 2015].

The analysis of monthly mean linear trend increments for air temperature and circulation indices for 2004–2016 detected the following features (Table 4):

- the maximum trend increment for air temperature is observed in February (+2.3°C);
- there is an increase in the western (W) circulation form and the NAO index with a decrease in the eastern (E) and meridional (C) circulation forms;
- the minimum trend increment for air temperature is observed in October, which is associated with a decrease in both the western (W) and the eastern (E) circulation forms and a maximum enhancement of the meridional (C) circulation form.

Conclusions

The changes in the air temperature characteristics for the Russian sector of the south-eastern

Table 4. Monthly Mean Values of Linear Trend Increment for Air Temperature, Western (W), Eastern (E), Meridional (C) Circulation Forms by Wangenheim-Girs, and the NAO Index

Month	Air temperature	W	E	C	NAO index
I	−0.6	−2.45	1.3	1.3	0
II	2.3	7.61	−10.99	−7.84	0.952
III	2.2	0.84	1.3	−2.14	0.602
IV	−0.3	1.92	−10.99	9.07	0.322
V	1.4	−1.46	5.15	−3.68	−0.238
VI	0.3	−12.0	8.06	3.92	0.182
VII	−0.1	−0.38	−0.84	1.22	−0.588
VIII	0.1	−12.6	3.99	−2.6	−0.336
IX	−0.3	10.9	7.46	3.46	−0.126
X	−2.1	−11.8	−2.91	14.76	0.602
XI	0.6	−4.84	6.15	−1.3	0.154
XII	−0.7	3.37	−1.37	−1.99	0.588

Baltic Sea in 2004–2017 (climatic half-period) was notable compared to the middle of the last century – the annual mean air temperature has increased (8.8 and 7.4°C respectively).

The annual minimum of air temperature shifted towards February (−0.3°C), which is associated with variations in the circulation conditions and indicates that the climate of the South-Eastern Baltic Sea has become more marine.

Variations of temperature in the cold period of year contribute greatly to the variability of annual mean values of air temperature.

The revealed variability of air temperature is closely associated with circulation conditions: a direct noticeable relationship ($r = 0.7$, p-level < 0.05) is established with the NAO index.

Deceleration of air temperature rise is caused by strengthening of the eastern circulation form along with a concurrent dominance of western circulation form.

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