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LONG-TERM VARIATIONS OF THE SEA LEVEL ON THE WESTERN COAST OF THE ANTARCTIC PENINSULA

ABSTRACT. The **aim** of the study is to analyze seasonal and interannual changes in sea level on the western coast of the Antarctic Peninsula. Objects of study are seasonal and interannual variability of sea level, air temperature, pressure at sea level, precipitation in the period 1960–2018 at the Faraday/Akademik Vernadsky station, which was considered as representative site for the Antarctic Peninsula. Statistical **methods** of study were used, including estimates of linear trends of time series using the nonparametric Sen's estimator of slope. The Mann-Kendall test was used to assess the significance of the slope of the trend. Time variability analysis was performed using wavelet analysis. Using the MATrix LABoratory (MATLAB) software package, squared of wavelet coefficients were calculated depending on the scale and shift or scalograms that characterize the local energy spectrum, and scalegrams calculated by averaging the scalograms by time shifts. The Morlet wavelet transformations were used. The **results** of the calculations showed that the trend of sea level at the Faraday/ Akademik Vernadsky station in the period 1960—2018, according to observations and correction on glacial isostatic adjustment of the crust is in the range from 3.05 to 3.45 mm/year, which is significantly higher than the global trend of 2.1 mm/year. Sea level scalograms allow estimating time-averaged periods and amplitudes of the coefficients for each season. In the austral winter and spring characteristic periods were 4—6 years, whereas the summer and autumn periods are characterized by 6–8 years, as well as by the highest amplitudes of the coefficients. All seasons are characterized by the appearance of a weakly pronounced period of about 4 years. The presence of peaks in the scalegrams at 6–8 and 3–4 years confirms the relationship of atmospheric and oceanic processes in West Antarctica to the natural variations of the ocean-atmosphere system, such as the Southern Annular Mode and El Niño-Southern Oscillation, which varies with typical 3–4 and 6–8 year periods. **It was concluded** that, unlike air temperature, the sea level trend is relatively weakly depends on the season, with the exception of autumn, when sea level trend is three times smaller than the average value. At the same time, the air temperature trend is the largest in the austral winter and the lowest in the summer.

Keywords: Antarctic Peninsula, Faraday/Akademik Vernadsky station, sea level, long-term variations, wavelet analysis.

INTRODUCTION

The Antarctic Peninsula (AP) and AP's western shelf waters have undergone significant climatic changes over the past 70 years. The raising of air temperature was near 3 °C (Vaughan et al., 2003; Stastna, 2010; Kravchenko et al., 2011; Tymofeyev, 2013), while the warming of the ocean surface layer was greater than 1 °C (Meredith and King, 2005). At the same time, these processes are not monotonous, and the absence of warming in the early 21st century observed at AP (Turner et al., 2016) was caused by natural fluctuations of the ocean-atmosphere system, such as the Atlantic Multidecadal Oscillation (AMO) (Li et al., 2015) with a period of several decades. More short

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term natural fluctuations (Southern Annular Mode (SAM) (Marshall, 2003; Hughes et al., 2003) and El Niño Southern Oscillation (ENSO) (Turner, 2004)) also have impact on the state of the atmosphere and the ocean in the AP shelf region.

Changes in the ocean level are an integral response to the various influences of the atmosphere, the ocean ice cover, glaciers, the Earth's crust response on changes in load on it in previous epochs, as well as changes in wind and thermohaline ocean circulation (Church et al., 2010). Against the background of continuous rise of the global sea level (CSIRO, 2015; EPA, 2018), important factors of regional changes in the sea level in the AP shelf region are the prolongation of the melting season and the corresponding enhancement of the melting of glaciers on the AP, the increase of precipitation and the freshening of coastal waters, which, together with the increase of the level due to the thermosteric factor, lead to halosteric rise in the sea level (Rye et al., 2014).

The analysis of long-term data series of sea level observations at Antarctic tide gauge stations showed the presence of interannual disturbances with periods of 2, 4—5, and 10—14 years, (Belevich et al., 2007/2008) and with periods of 4 and 9 years (Galassi and Spada, 2017). The relationships between inverse barometer corrected sea level, Drake Passage transport and SAM were studied by Woodworth et al. (2006). In this article, the analysis was supplemented with data up to 2018 (incl.) and also expanded by including processes for each of the 4 Antarctic seasons, for which trends and the contribution of relevant fluctuations to the annual average may significantly differ. The seasonal and interannual variability of sea level, air temperature and pressure at the Ukrainian Antarctic Akademik Vernadsky station for which there are the longest series of level observations (1958—2018) are also considered. These data include observations at the Faraday Base of the British Antarctic Service in 1958—1996. Unlike studies that used spectral analysis (Belevich et al., 2007/2008) and decomposition by empirical orthogonal functions (Galassi and Spada, 2017), this study uses the wavelet decomposition to analyze the changes over time of the contribution of different components of the decomposition.

MATERIALS AND METHODS

This study used the results of observations of sea level at the tide gauge stations on the Antarctic Peninsula shown in Fig. 1. The list of stations and availability of data from the database Permanent Service for Mean Sea Level (PSMSL, 2019; Holgate et al., 2013), according to the requirements Revised Local Reference (RLR), is shown in Table. 1. Time series of average monthly air temperature, sea level pressure, precipitation, sea surface temperature and salinity at the Faradey/Akademik Vernadsky station were also used for analysis.

A nonparametric method was used to estimate the slope of the linear trends of the time series (Sen, 1968) where slope of the trend was calculated as median of the slopes of all lines through pairs of points. The Mann-Kendall test (Mann, 1945; Kendall, 1970) was used to estimate the significance of the slope of the trend.

The variability analysis of time series $f_k = f(t_k)$, $k = 1, \ldots N$ was conducted by using of the wavelet analysis (Scargle,1997; Torrence and Compo, 1998). The wavelet coefficients $W_A(a_i, b_j)$ were calculated using the MATLAB software package with Morlet function

$$\psi(\tau) = \exp(-\tau^2/2)\cos(5\tau), \quad (1)$$

where τ is nondimensional time parameter (MATLAB, 2019). The parameter a_i is the scale of wavelet whereas parameter b_j is the shift of the wavelet localizing wavelet in time. Scale and shift of energy distribution is described by a scalogram

$$S(a_i, b_i) = \left|W_A(a_i, b_i)\right|^2. \quad (2)$$

Wavelet spectrum estimates, or scalegrams, were calculated by averaging on shifts the scalograms (Scargle, 1997).

$$SC(a_i) = \frac{1}{N}\sum_{k=1}^{N} S(a_i, b_k). \quad (3)$$

RESULTS

The using of the Antarctic tide gauge stations for long-term estimation of sea level changes is complicated by several factors. The most important are the

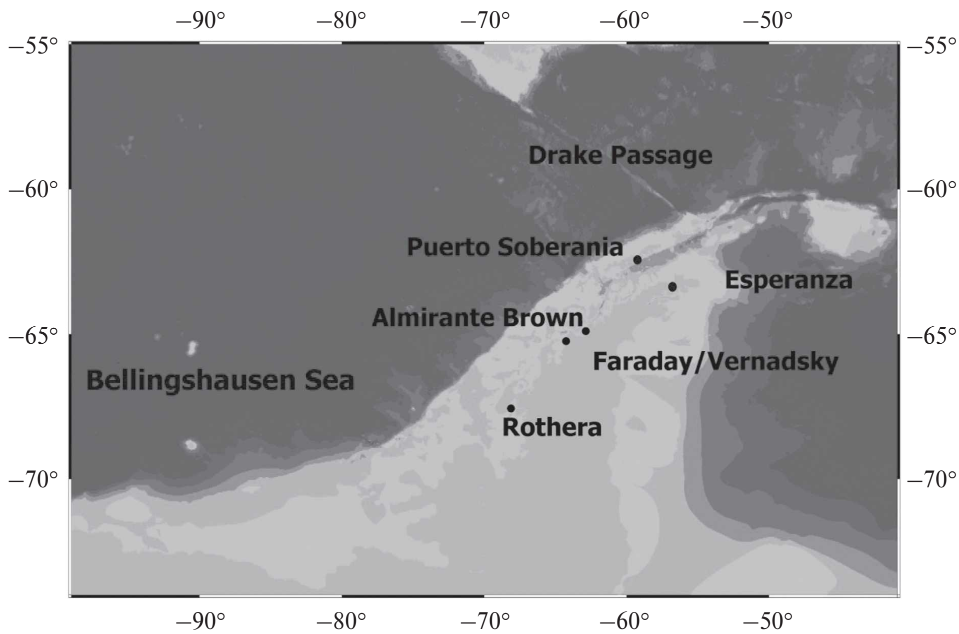

Fig. 1. Bellingshausen Sea, Antarctic Peninsula and Drake Passage, as well as positions of tide gauge stations in the Antarctic Peninsula area

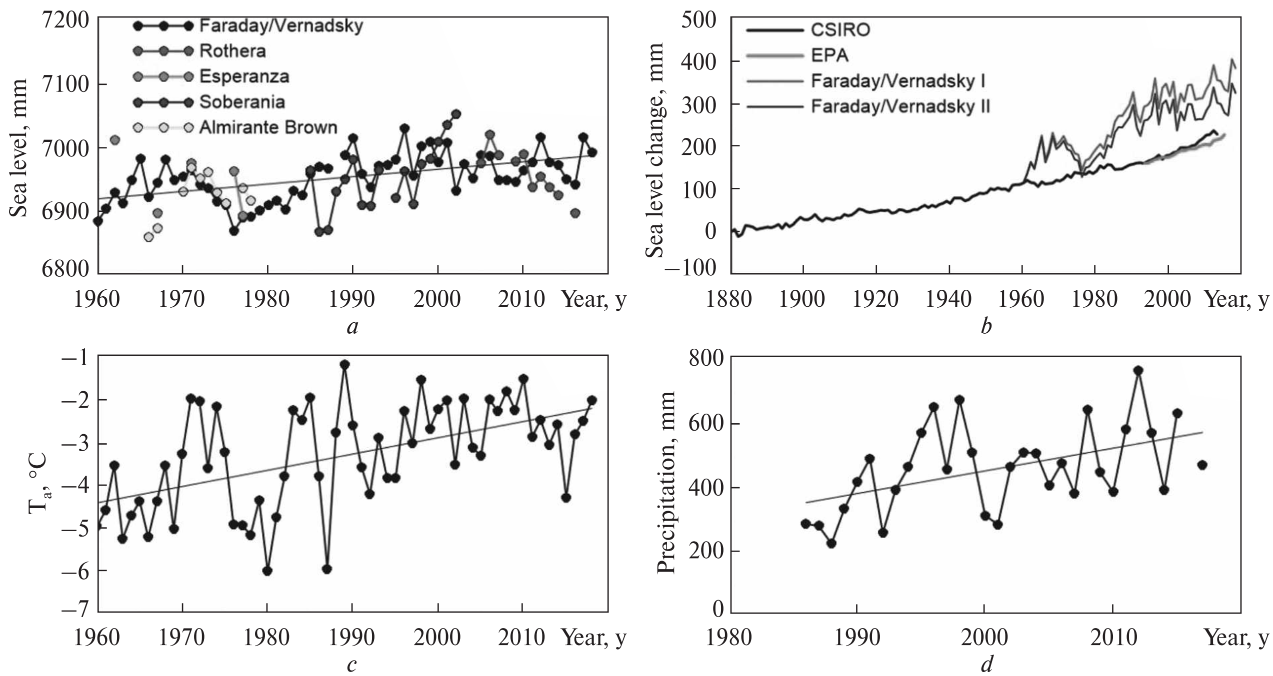

Fig. 2. Changes of the annual sea level at the Faraday/Akademik Vernadsky station with the imposed changes of sea level at other stations of Antarctic Peninsula (*a*), global change of sea level (CSIRO, 2015; EPA, 2018) with imposed elevation at the Faraday/Akademik Vernadsky station corrected for GIA using models I (Peltier et al., 2015) and II (Whitehouse et al., 2012) (*b*), change of the annual surface air temperature (*c*) and precipitation (*d*) at the Faraday/Akademik Vernadsky station

absence of long-term series of observations, breaking in measurements and loss of tide gauge zero point due to various reasons. According to the Table 1, the continuous time series at stations are relatively short with exception of Akademik Vernadsky station (Argentine Islands, Faraday/ Akademik Vernadsky station), where the duration of the time series was 61 years. The corresponding level values on Puerto Soberania, Rothera, Bahia Esperanza and Almirante Brown stations were adjusted, so that mean values of the continuous observation segments at these stations coincided with the mean of the corresponding the Faraday / Akademik Vernadsky station time series segments. As shown in Fig. 2, *a*, the temporal level distributions at the other stations and at the Faraday/ Akademik Vernadsky station were close, characterizing the distribution at the Faraday/Akademik Vernadsky station as representative for all AP area. Therefore, a further analysis of the changes in the level was carried out using the data of the Faraday/ Akademik Vernadsky station, as opposed to (Galassi and Spada, 2017), where a series of data from all AP region stations was analyzed.

Trends of the average annual values of sea level, air temperature and precipitation at the Faraday/Akademik Vernadsky station are shown in Fig. 2, *a, c, d*. The corresponding trend of sea level evaluated by the nonparametric method (Sen, 1968), is +1.23 mm/ year with a significance level of 0.01. Sea level observed at tide gauge stations should be adjusted by the isostatic rate of rise or fall of the Earth's crust (Glacial Isostatic Adjustment, GIA) as a result of changes in its load during melting or freezing of the glaciers. Several models have been developed for GIA estimation, which according to (Galassi and Spada, 2017) gave values from –2.2 mm/year (model I (Peltier et al., 2015)) till –1.8 mm/year (model II (Whitehouse et al., 2012)). Thus, the trend of sea level in the period 1960—2018 according to observations and correction due to GIA is in the range from 3.05 to 3.45 mm/ year, which correspond with estimates (Galassi, Spada, 2017). This value is higher than the global trend

Table 1. **Tide gauge stations on the Antarctic Peninsula and its islands**

Station name according to PSMSL	Code PSMSL	Latitude	Longitude	Period (years)	Duration (years)
Argentine Islands (Faraday /Akademik Vernadsky station)	913	–65.246	–64.257	1958—2018	61
Puerto Soberania	1603	–62.483	–59.633	1985—2002	18
Rothera	1931	–67.571	–68.130	2003—2018	16
Bahia Esperanza	1889	–63.300	–56.917	1962—1972	5
Almirante Brown	858	–64.900	–62.867	1958—1978	11

Table 2. **Estimated trends of sea level, air temperature and sea level pressure. The asterisks show significance levels of 0.1, 0.05 and 0.01, respectively**

Parameter	Winter JJA	Spring SON	Summer DJF	Autumn MAM	Average value
Sea level (mm/y)	+1.43***	+1.18**	+1.64***	+0.496	+1.23***
Air temperature (°C / y)	+0.080***	+0.023*	+0.018**	+0.035***	+0.039***
Sea level pressure (mm/ y)	–0.046	–0.011	–0.069***	+0.011	–0.029*

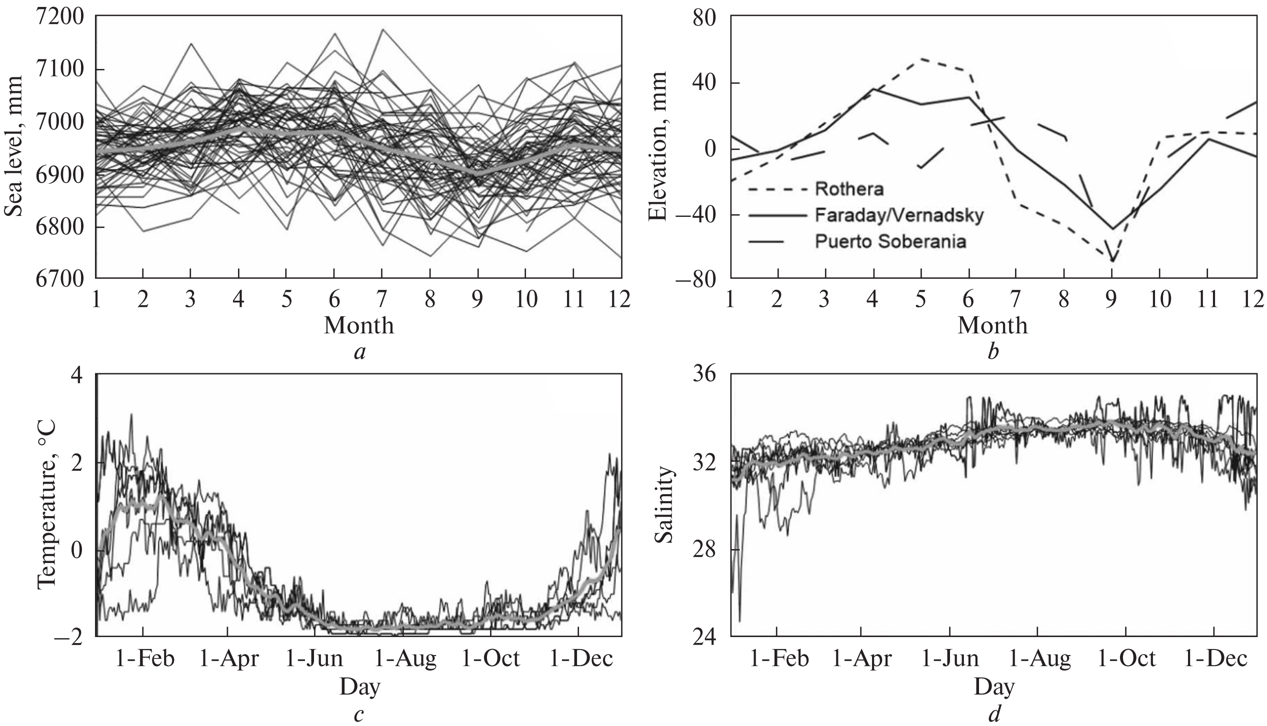

Fig. 3. Seasonal variations of mean month sea level at the Faraday / Akademik Vernadsky station during the period 1960–2018 (*a*), ten-year averaged mean month variations of elevation from mean sea at tide gauge stations located at AP (*b*), seasonal variations of sea surface temperature (*c*) and salinity (*d*) at the Faraday / Akademik Vernadsky station

of +2.1 mm/year (EPA, 2018) in the same period. At the same time, for the period 1997–2014 adjusted by GIA trend for the Faraday/Akademik Vernadsky station was of 1.8–2.2 mm/year, while the global trend according to data from observations at tide gauge stations (EPA, 2018) was of 3.9 mm/year, and the trend according to satellite observations in the period 1993-2015 was of 2.8 mm/year (EPA, 2018). Fig. 2, *b* shows changes of global level according to (CSIRO, 2015; EPA, 2018) with imposed level changes at the Faraday/Akademik Vernadsky station adjusted on GIA. As can be seen in Fig. 2, *b*, local changes in the level in the Antarctic Peninsula region are significantly different from changes in the global level, which may be related to local melting processes in the West Antarctica due to the rise of air temperature, which also causes the halosteric rise of the level due to the corresponding freshening of the ocean waters (Rye et al., 2014).

The evolution of average annual air temperature at the Faraday/Akademik Vernadsky station during the period 1960–2018 is shown in Fig. 2, *c*. Observations showed that over the past 70 years the temperature has risen by an average of 3.3 °C. The corresponding trend is +0.047 °C /year. But for the period 1997–2014 the trend becomes negative (–0.01 °C /year) according to the so-called hiatus in the global warming due to natural fluctuations (Turner et al., 2016). Evolution of annual precipitations at the Faraday/Akademik Vernadsky station during the period 1986–2017 is shown in Fig. 2, *d*. Observations show an increase in precipitation of 253 mm in average. The corresponding trend is +7.6 mm/year. Unlike the evolution of temperature, the trend for the period 1997–2014 does not become negative, although its value decreases (+5 mm/year).

Seasonality of processes is an important factor in long-term climate change. Seasonal sea level distribution at the Faraday/Akademik Vernadsky station during the period 1960–2018 is shown in Fig. 3, *a*. It differs from the temperature and salinity distribution

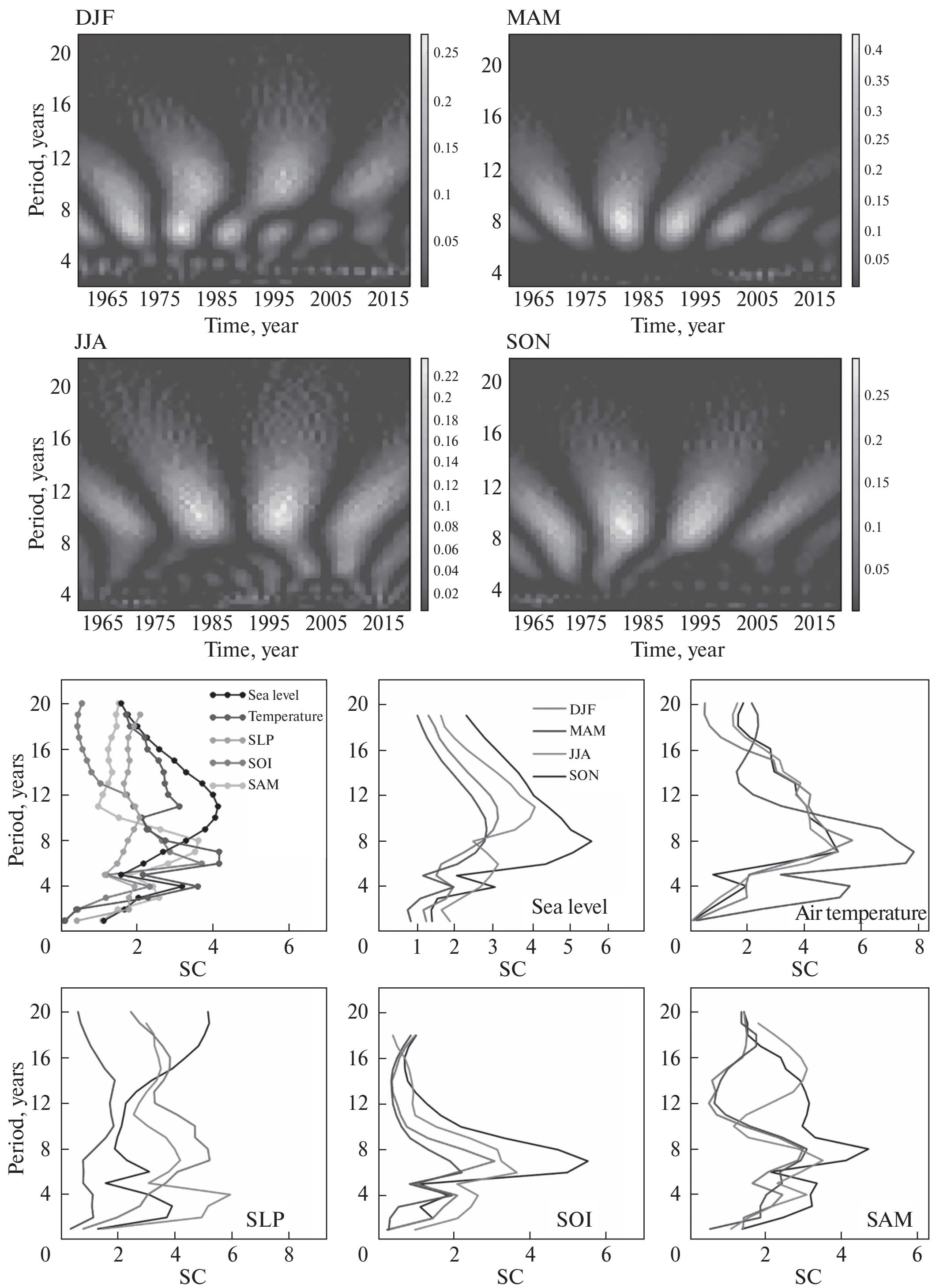

Fig. 4. Sea level scalograms for different seasons (*a—d*), average yearly scalegrams of sea level, air temperature, sea level pressure (SLP), Southern Oscillation Index (SOI) and Southern Annular Mode Index (SAM) (*e*), seasonal sea level, air temperature, SLP, SOI, and SAM scalegrams (*f—j*)

in Fig. 3, *c, d* by the presence of significant fluctuations in the average monthly values of the level, which is caused mainly by dynamic processes in the ocean under the influence of variable wind systems. Seasonal variation of sea level at the Faraday/Akademik Vernadsky station has amplitude of approximately 80 mm with the minimum at the end of austral winter and the maximum in April (austral autumn). As seen in Fig. 3, *b*, the seasonal variations of the level at AP stations are similar. It is caused by both the inflow of freshened waters from the mainland and the increase in water temperature, which leads to thermosteric and halosteric sea level changes. This process is not local and covers a large area of the Bellingshausen and Amundsen seas (Rye et al., 2014), which is confirmed by the presence of a delay of about 4 months between the maximum of the surface temperature and the minimum of salinity in Fig. 3, *c, d* and the maximum level in Fig. 3, *a, b*.

Fig. 3, *c* shows the seasonal distribution of sea surface temperature at the Faraday/Akademik Vernadsky station during the period 2009–2017. The average temperature changes from +1 °C to –1.8 °C (freezing temperature of seawater). Seasonal variations correspond to the open water conditions of austral summer and autumn (1–150 days), the presence of ice cover in austral winter and spring (150–300 days) and again open water conditions (300–365 days). The maximum water temperature was observed in 2009. Seasonal distribution of sea surface salinity at the Faraday/Akademik Vernadsky station during the period 2003–2017 is shown in Fig. 3, *d*. Salinity during the year varies, on average, in the range 32.0–32.5 with a maximum during the austral winter and a minimum during the austral summer. Abnormally low salinity values were observed in 2017. This phenomenon is not related to water temperature anomalies and, accordingly, local ice melting processes. It can be assumed that this anomaly is caused by the appearance of a lens of freshened water from the coastal area.

In the presence of significant seasonal variations in the state of the sea and the atmosphere, it should be expected differences in the trends of the relevant parameters at the AP. Table 2 shows the sea level trends, air temperature and sea level pressure at the Faraday/Akademik Vernadsky station for four austral seasons: winter (June, July, August (JJA)), spring (September, October, November (SON)), summer (December, January, February (DJF)), autumn (March, April, May (MAM)). As follows from Table 2, the trend of level is relatively weakly depends on the season, except in the autumn, when it is three times less than the average. At the same time, the trend of temperature is maximal in the austral winter and the minimal in the summer, which is well known in climate research (Vaughan et al., 2003; Stastna, 2010; Kravchenko et al., 2011). Trend estimates in Table 2 gives slightly lower values of winter warming rate (+0.08) than earlier work (+0.11) due to the inclusion in the analysis of the global warming hiatus period 1995–2014. Seasonal pressure trends at sea level given in Table 2 are statistically insignificant, with the exception of the negative trend in the summer.

Wavelet analysis allows to identify the concentration of a signal on a certain scale and to track its time evolution. Fig. 4, *a–d* shows the sea level scalograms calculated for 4 seasons depending on the scale and the period. The values of the scalograms are normalized on their sum. Note that due to the influence of the edge effects of the analyzed series, only periods less than 20 years are shown. As shown in Fig. 4, *a–d*, the scalograms varied both by the periods and amplitudes for each season. All seasons are characterized by periods of 6–8 years and mild period of about 4 years. More long-term fluctuations (about 10 years) appeared in 1975–2015.

The sea level scalegrams (Fig. 4, *f*) allow estimating the shift-averaged periods and the amplitudes of the coefficients for each season. Since the coefficients are calculated on a discrete sequence, errors near the boundary are possible due to the inability to use the entire length of the analysing wavelet. The highest amplitudes of level scalegrams were observed in the austral spring with a maximum over a period of 8 years. For winter and summer, the period corresponding to the maximum of the *SC* was 10 years. For all seasons except summer, the presence of a weakly pronounced period of about 4 years is typical. Air temperature scalegrams (Fig. 4, *g*) are generally similar to the sea level scalegrams, with higher amplitude in the autumn and a blurred maximum of about 8 years. Unlike sea level and temperature scalegrams, sea level pressure scalegrams have a maximum of 3–4 and 6 years, whereas the largest amplitudes of wavelet coefficients are observed in winter and spring. The presence of maximums in the scalegrams of marine and atmospheric parameters on AP for the period of 6–8 years and 3–4 years confirms the relationship between processes in the atmosphere and ocean in West Antarctica with the natural fluctuations of the ocean-atmosphere system, such Southern Annular Mode (SAM) and El Niño Southern Oscillation (ENSO), which have typical periods of 6–8 and 3–4 years (Turner, 2004; Stastna, 2010; Kravchenko et al., 2011; Clem and Fogt, 2013). Scalegrams of sea level, air temperature, and sea level pressure mean annual values, as well as mean annual values of the Southern Oscillation Index (SOI) and Southern Annular Mode Index (SAM) are shown in Fig. 4, *e*. Maximum values of SOI are observed in periods of 6 and 4 years, whereas a maximum of SAM exists for a period of 4 years and 6–8 years. The corresponding maximums of annual mean scalegram of the sea level are of about 4 and 10 years that agree with estimate 9 year obtained by Galassi and Spada (2017) using decomposition by empirical orthogonal functions. Maximums in air temperature scalegrams occur over periods of 4, 6, and 10–16 years, which is consistent with the results (Kravchenko et al., 2011), whereas the sea level pressure maximum corresponded to a period of 3–4 years.

The Pearson correlation coefficient r was used to estimate the linear correlation between sea level scalegrams for different seasons and SOI and SAM scalegrams. The correlation coefficients between SOI and the sea level scalegrams for the austral winter (JJA) and spring (MAM) were –0.53 and –0.59, respectively, whereas for other seasons the relationships were statistically insignificant. At the same time, the correlation coefficients between scalegrams of SAM and the sea level for all seasons were in range of 0.64—0.68.

CONCLUSIONS

The results of the calculations showed that, according to the observations and correction due to isostatic velocity of raising or lowering of the Earth's crust, the trend of sea level at the Faraday/Akademik Vernadsky station during the period 1960–2018 is in the range from +3.05 to +3.45 mm/year, which is significantly higher than the global sea level trend of +2.1 mm/year. Unlike the air temperature, the sea level trend is relatively weak depending on the season, except in autumn, when it is less than three times compared to the average, which is explained by the influence not only of seasonal changes in water temperature and salinity, but also of seasonal changes in the wind component of ocean circulation. At the same time, the air temperature trend is maximal in the winter and minimal in the summer. Sea level scalegrams built using wavelet analysis allowed to estimate shift-averaged periods and wavelet coefficient amplitudes for each season. The highest amplitudes of sea level scalegrams were observed in the spring with a maximum over a period of 8 years. For all seasons except summer, the presence of the weakly pronounced period of about 4 years is typical. Presence of maximums in scalograms and scalegrams of sea level, air temperature and pressure at sea level for 6–8 and 3–4 years periods confirms the relationship between processes in the atmosphere and ocean in Western Antarctica with the natural fluctuations of the ocean-atmosphere system, such as Southern Annular Mode (SAM) and El Niño Southern Oscillation (ENSO), which have typical periods of 6–8 and 3–4 years. Further studies need to be supplemented by modeling the regional circulation of the Bellingshausen and Amundsen seas along with the adjacent AP shelf to evaluate the contribution of level changes under the influence of dynamic factors and thermosteric and halosteric factors in different seasons.

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ДОВГОСТРОКОВІ ВАРІАЦІЇ РІВНЯ МОРЯ НА ЗАХІДНОМУ УЗБЕРЕЖЖІ АНТАРКТИЧНОГО ПІВОСТРОВА

РЕФЕРАТ. **Метою** дослідження є аналіз сезонних і багаторічних змін рівня моря на західному узбережжі Антарктичного півострова. Об'єкт дослідження: сезонна і міжрічна мінливість рівня моря, температури повітря, тиску на рівні моря, опадів на станції Фарадей/антарктична станція «Академік Вернадський» в період 1960—2018, яка розглядалась репрезентативною для Антарктичного півострова. Використовувалися статистичні **методи** дослідження, що включають оцінки лінійних трендів часових рядів за допомогою непараметричного методу Сена. Тест Манна – Кендала застосовувався для оцінки рівня значущості нахилу тренду. Аналіз часової мінливості проводився за допомогою вейвлет–аналізу. З використанням пакету програм Матлаб (Matrix Laboratory, MATLAB) розраховувались квадрати коефіцієнтів вейвлетів в залежності від масштабу та зсуву або скалограми, які характеризують локальний спектр енергії, та скейлограми, розраховані осередненням скалограм по часовим зсувам. Для вейвлет-перетворень використовувались функції Морле. **Результати** розрахунків показали, що тренд рівня моря на станції Фарадей/антарктична станція «Академік Вернадський» в період 1960–2018 рр. згідно зі спостереженнями та корекцією за рахунок ізостатичної швидкості підйому або опускання земної кори знаходиться в діапазоні від 3.05 до 3.45 мм/рік, що значно вище ніж глобальний тренд рівня 2.1 мм/рік. Скейлограми рівня моря дозволяють оцінити осереднені по зсувам періоди і амплітуди коефіцієнтів вейвлетів для кожного сезону. Найбільші амплітуди скейлограм рівня моря спостерігались австральною весною з максимумом на періоді 8 років, але в середньому за рік максимум амплітуди спостерігається на періоді 10 років. Для всіх сезонів характерна наявність слабо вираженого періоду близько 4 років. Наявність максимумів у скейлограмах рівня моря, температури повітря та тиску на рівні моря на періодах 3–4 роки і 6–8 років підтверджує зв'язок процесів в атмосфері і океані в західній Антарктиці з природними коливаннями системи океану-атмосфери, таких як Південна Кільцева Мода та Ель-Ніньйо-Південне Коливання, які мають характерні періоди 3—4 та 6—8 років. Зроблено **висновок**, що, на відміну від температури повітря, тренд рівня відносно слабко залежить від сезону, за винятком осені, коли він менше в три рази в порівнянні із середньорічним, тоді як тренд температури найбільший австральною зимою і найменший влітку.

Ключові слова: Антарктичний півострів, станція Фарадей/антарктична станція «Академік Вернадський», рівень моря, довгострокові варіації, вейвлет-аналіз.